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Zero net carbon model for Victorian houses

Ian McNicol[a]*, Robert Foster[b]

[a]*Sustainability Victoria, Level 28, 50 Lonsdale Street, Melbourne, 3000, Australia*
[b]*Energy Efficient Strategies, 1629 Old Sale Road, Blun Blun East, 3821, Australia*

** Corresponding author. Tel.: +613-8626-8772; E-mail address:* ian.mcnicol@sustainability.vic.gov.au

Abstract

The paper describes the Zero Net Carbon (ZNC) modelling tool developed by Energy Efficient Strategies for Sustainability Victoria, and discusses approaches to upgrading Victorian houses to achieve zero net emissions over a year, based on their household energy consumption and electricity generation from rooftop PVs. The ZNC tool is highly flexible and allows both a 'base' and an 'improved' house to be modelled for various combinations of house size, building shell efficiency, climate, occupancy, fuel source, appliance mix and efficiency, rooftop PVs and battery storage. Hourly energy consumption over a full year is modelled for both the base and improved houses, as well as the electricity generation of any PVs present, and the interaction between the battery, PVs and electricity consumption. Outputs are provided for each house in the form of energy, greenhouse gas emissions, energy bills, in both annual and daily profiles. The tool calculates the additional cost of the improvements, the energy bill savings over a specified period, and the NPV and benefit-cost ratio. It also calculates the size of the rooftop PV system required to achieve a zero net carbon status for the improved house.

Keywords: carbon neutral houses; residential energy efficiency; photovoltaic (PV) systems; battery storage

1. Introduction

The ZNC tool was developed for Sustainability Victoria (SV) by Energy Efficient Strategies (EES) and IT Power Renewable Energy Consulting to allow the practicality, costs and benefits of zero net carbon houses to be explored for both existing and new Victorian houses. A "zero net carbon" status is achieved if the modelled house has zero net greenhouse gas emissions over a typical year based on energy used by appliances and lighting in the house and electricity generated by rooftop PVs, which off-set the greenhouse gas emissions of the energy used in the home. Key questions that the model can answer are:

- What range of improvements are required for a standard existing or new house to achieve ZNC status?
- What will it cost to achieve ZNC status, both in the short term (current prices) and longer term, taking "learning effects" into account?
- The benefits of achieving ZNC status, in terms of energy, energy bill and greenhouse gas savings;
- The economics of upgrading to a ZNC status, and the impact that battery storage has on this; and
- The impact of the improvements on the daily energy demand profile of the house throughout the year.

The ZNC tool brings together consideration of energy efficiency with on-site PV generation, battery storage and energy tariffs, and provides outputs relating to the costs, energy and greenhouse savings, and daily energy demand profile implications of the upgrades modelled. SV will use it to develop information resources for householders, the building industry and the energy services sector, and to support wider policy thinking within government. The tool will help us to identify the package of measures that makes sense from the householder perspective, and that supports government's longer term environmental and energy system goals.

Nomenclature

ZNC	Zero Net Carbon – zero net emissions over a year based on energy use and PV generation
HER	House Energy Rating – rating from 1 to 10 stars using a thermal modelling tool such as Accurate

2. Overview of the ZNC tool

A schematic diagram of the ZNC modelling tool is shown in Figure 1. It has been constructed as a MS-Excel workbook designed to be transparent in its operation and user friendly. A 'Control Panel' worksheet allows the tool user to interact with the model by: - selecting parameters for the base and improved houses that are modelled, specifying the financial modelling parameters and technical details of the PV and battery storage and selecting the format of the outputs provided (see below for details). It also provides some of the main output charts and tables.

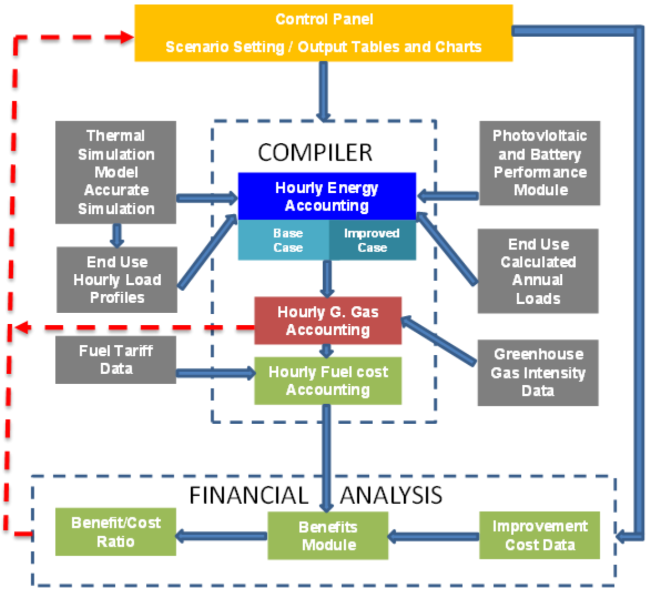

Figure 1: Schematic diagram of the ZNC tool

At the heart of the ZNC model is the 'Compiler'. This takes inputs from a range of separate modules and estimates the hourly energy consumption, by fuel, for all end-uses modelled for both the base and improved houses over an entire (typical) year. It combines this with greenhouse gas coefficients to estimate annual greenhouse gas emissions, and energy tariffs to estimate annual energy costs. This allows a comparison of the base and improved houses to be made for these outputs, either annually or over a specified time period.

The 'Thermal Simulation Model' is based on Accurate thermal modelling of the small, medium and large house types included in the tool, and is the basis of the heating and cooling loads used. The thermal modelling has been undertaken for the three main Victorian climate types, a range of building shell efficiency levels, and for two common occupancy profiles. The modelling generates hourly heating and cooling loads throughout the year. Within the compiler this load data is combined with the user specified data on the heating/cooling system type and efficiency to estimate the fuel consumption for heating and cooling for each hour of the year.

The 'End Use Calculated Annual Loads' module calculates the hourly energy use throughout the year for lighting and all other end-uses. Separate models are used for each appliance type, and these take into account the energy efficiency of the appliance, and their likely energy consumption profile during the year. Firstly, an estimate of annual energy consumption is made using a calculator developed by EES for SV in 2015 [2]. Secondly, the annual energy consumption is allocated across each hour of the year. The hourly profiles used for each appliance are based on a Pacific Power study undertaken during the 1990s [3], supplemented by data from a number of SV's recent end-use metering studies. Depending on the appliance type (e.g. water heating, clothes washer, etc.), the energy consumption calculation also takes into account the number of house occupants.

The 'Photovoltaic and Battery Performance' module, developed by EES with the assistance of IT Power Renewable Energy Consulting, operates in parallel with the Compiler and estimates the hourly electricity input from any rooftop PV array present. These estimates are based on the same hourly Accurate climate file data used to estimate the heating and cooling loads. This use of common weather data provides a realistic simulation of the interplay between the PVs, batteries and electrical loads within the house. For each hour of the year the module calculates how much of the PV generation is stored in any batteries (if present), how much is exported to the grid, and how much electricity must be imported from the grid to meet household demand. From this data the energy cost savings/earnings and greenhouse gas emission savings associated with the PV/battery set-up are made.

The 'Financial Analysis' module calculates the costs and savings of the upgrade from the base to the improved house. Account is taken of the need to replace some elements of these systems on a regular basis (e.g. PVs every 20 years and inverters every 10 years). The annual energy bill saving is calculated, as well as the present value of the upgrade costs and the savings over the analysis period. The benefit-cost ratio (BCR) is also calculated. The building shell upgrade costs are based on SV's *On-Ground Assessment* study [4] for existing houses, and on unpublished research undertaken by EES and Tony Isaacs Consulting in 2009 for new houses. Appliance upgrade costs are based on EES research using a range of sources, including their analysis of Gfk appliance sales data [5], installers and on-line sales sites. This data was used to establish relationships between efficiency level and price for a particular capacity, and this was used to estimate the cost of the appliance upgrades selected. The costs associated with the supply and installation of PV panels and inverters were based on data obtained from www.solarchoice.net.au and take into account the value of any STCs. The battery storage costs and projections of future price changes for PVs and battery storage were developed by IT Power Renewable Energy Consulting.

The degree to which a house meets the ZNC target is estimated in the Compiler. This is expressed as the total abatement (due to the improvements) divided by the greenhouse gas emissions of the base house. A value of 100% means the house meets the ZNC target. A value of less than 100% means the house falls short of the target and a value greater than 100% means the house exceeds it. ZNC status is simultaneously calculated for a range of PV array sizes from 1 kW to 10 kW and interpolation is used to determine the exact size of the PV array required for the improved house to meet the ZNC standard.

A range of output charts and tables are provided by the tool for both the base and improved house – outputs based on greenhouse gas emissions, energy use or energy bills can be selected. The charts show the results for each month of the year, broken down by the main end-uses modelled. The average daily profile for each hour of the day can also be selected for any month of the year.

3. Modelling options

The ZNC tool is a very flexible scenario modelling tool that provides a wide range of options when specifying the base and improved houses, as well as in the financial modelling parameters and technical parameters of the PV and battery storage system. The main options available are described briefly below.

Houses modelled

- House size – options are detached small (113 m^2), medium (188 m^2) and large (265 m^2). The house designs used are from the Victorian housing stock model developed by Tony Isaacs for SV [1];
- Number of occupants - the default number is based on house size – small (2 people), medium (3) or large (4) – these default values can also be overridden by the user;
- Climate zone – Mild (Moorabbin 62), Cold (Ballarat 66) or Hot (Mildura 27);
- House occupancy profiles – either a 'home all day' or 'work day' occupancy schedule;
- Building shell performance, based on HERS rating – Existing houses can be either 2 Stars (the approximate average for pre-2005 houses) or a 5 Stars (minimum standard 2005 to 2010). New houses can be either 6 Star (current minimum standard), 7 Star or 8 Star;
- Energy end-uses - the options included and separately modelled are heating, cooling, water heating, cooking, lighting, refrigerators, freezers, clothes washers, dishwashers, clothes dryers, televisions, swimming pool pumps and heating, standby power and miscellaneous (all others). The user can select the type and number of appliances included or can select from a number of pre-configured "appliance schemes", such as "Mixed gas and electric / Central Gas heating / Room HP cooling / No Pool";
- Fuel choice - where relevant (e.g. heating and water heating), this can be based on electricity (including various mixes of "green power"), mains gas, LPG or firewood;
- Energy tariffs – defaults are based on 2016 Victorian averages, and the user can override these. Different tariffs can be selected for the base and improved house. Five types of tariff are specified for electricity: - peak, shoulder, off-peak, green power premium (% of greenpower used can be specified), and feed-in (for houses with PVs). The tariff scheme selected can be either 'flat rate' (peak and off-peak, where relevant) or 'Time-of-Use' (peak, shoulder, off-peak); and,
- Scope of the ZNC calculation - the default option is for this to cover all energy used in the home, or it can be limited to just fixed appliances. It is also possible to individually select the end uses to be included in the scope of the calculation.

Equipment performance

- The efficiency level of the stock of all lighting and appliances can be specified as either 'stock average' (average of equipment currently found in houses), 'market average' (average of new equipment currently sold) and 'best in market' (highest efficiency currently available). In addition to specifying the general level of efficiency, the user can override the default settings for any of the end uses; and,

- Rooftop PVs – none, or 1 kW to 10 kW systems in 1 kW increments. Battery storage – none, or 2 kWh to 20 kWh in 2 kWh increments. The user can also manually set any capacity of the PV or battery storage systems.

Financial settings

- Year of commencement of the economic analysis – 2016 up to 2025;
- Timeframe for the economic analysis – 10 to 100 years, in 10 year increments;
- Fuel costs (2016) and their expected real rate of annual increase or decrease. The default is 1%;
- Discount rate for the NPV analysis. The default is 3%, but 0%, 5% or 7% can be selected, or a value input;
- Learning rate – the assumed annual rate of change in the real cost of the building shell and appliance upgrades, PVs and batteries. The default is -2%, except batteries (-10%). The time (in years) over which these learning rates apply can also be set – after which they are set at 0%; and,
- Value per STC (small scale technology certificate) awarded for PV systems, and the number of STCs per kW of installed PV.

4. Achieving a ZNC status for Victorian houses

We have used the ZNC tool to model a range of scenarios for new and existing houses located in Victoria. In this paper we present modelling results for a medium house located in Melbourne occupied by 3 people with a 'work day' occupancy profile. The houses are assumed to be mixed gas (heating, water heating, and cooktop) and electric, with gas central heating and a room air conditioner used for cooling. It is assumed that the improvements occur in 2017, and a 40 year analysis period has been chosen with a 3% discount rate. The key differences between the base house and the reference improved ZNC house are shown in Table 1. Except where noted in Table 1 the houses have the default set of appliances for the appliance scheme chosen, although they do not have a secondary refrigerator or a swimming pool. All other settings used for the modelling are the tool's default settings.

Table 1. Base and improved houses modelled.

House	Base house	Improved house (reference)
New	6 Star HERS rating, gas-boosted solar water heater, market average appliances	8 Star HERS rating, gas-boosted solar water heater, market average appliances, 2.9 kW of rooftop PV. No battery storage.
Existing	2 Star HERS rating, stock average appliances, gas storage water heater	5 Star HERS rating, market average appliances, gas instantaneous water heater, 3.9 kW rooftop PV. No battery storage.

Table 2. Summary of key modelling outputs for each house.

Output parameter	New house	Existing house
Annual results		
Annual energy cost savings ($/yr)	$708	$1,673
Annual greenhouse gas emission savings (tonnes $CO_{2\text{-}e}$/yr)	5.76	11.20
% ZNC status attained	102%	100%
Present value of lifetime costs (3% discount)		
Building shell improvements	$3,766	$15,845
Appliance upgrades	-	$4,880
Rooftop PV	$9,096	$11,204
Total cost of improvements	*$12,862*	*$31,929*
Present value of lifetime savings (3% discount)		
Building shell improvements and appliance upgrades	$6,194	$28,410
Rooftop PV	$11,908	$14,100
Total savings from improvements	*$18,002*	*$42,510*
Benefit-cost ratio	1.40	1.33

The key outputs from modelling the ZNC upgrade scenarios shown in Table 1 are provided in Table 2. As expected, the cost of achieving ZNC status is much higher for the existing house compared to the new house, due to the much higher greenhouse abatement required. In particular, the cost of the building shell improvements are much higher for the existing house, with additional costs related to the appliance efficiency upgrades and a larger PV system. For the new house, the building shell improvement cost is lower than adding the rooftop PVs, and provides a better benefit-cost ratio – 1.64 for the building shell improvement compared to 1.31 for the PVs. For the existing house, while the building shell and appliance improvements (NPV of $20,725) are more expensive than the rooftop PVs, they also have a better benefit-cost ratio – 1.37 compared to 1.26.

4.1. Detailed results for the new Victorian house

The base new house modelled had estimated annual greenhouse gas emissions of 5.63 tonnes $CO_{2\text{-e}}$/yr, and annual energy costs of $1,427/yr, due to electricity consumption of 3,243 kWh/yr and gas consumption of 28,094 MJ/yr. The main greenhouse gas emission output charts from the tool are shown in Figure 2 for the reference upgrade scenario (similar charts are available for energy use and energy costs). The charts show the total emissions in each month of the year broken down by the main energy end-uses. For the improved case (right hand chart) the greenhouse offset provided by the rooftop PV is shown as a red line, being higher than the emissions from energy end-use during the summer months, and lower during the winter months. The impact of the building shell upgrade is also evident in the chart for the improved house, with monthly emissions being lower than for the base house, especially during winter due to the lower heating energy demand.

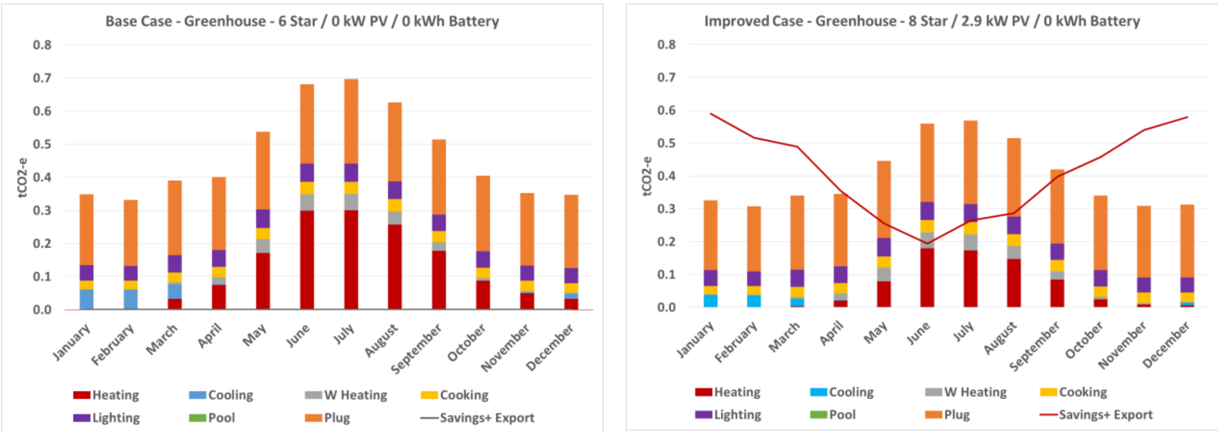

Figure 2: Greenhouse gas emissions from base and improved new house, by month of the year

Figures 3 (January) and 4 (July) provide examples of the average daily profile data available for each month of the year. In this case they are based on greenhouse gas emissions during each hour of the day, broken down by the different energy end-uses. The red line on the chart for the improved house shows the average greenhouse offset provided by the rooftop PV system when generating electricity. A comparison of Figures 3 and 4 highlights the large difference between energy consumption during January and July, mainly due to heating. The graphs also show that the offset provided by the PV system occurs during those hours of the day when energy demand is fairly modest, and therefore this offset exceeds the energy related greenhouse gas emissions, especially in January but also in July.

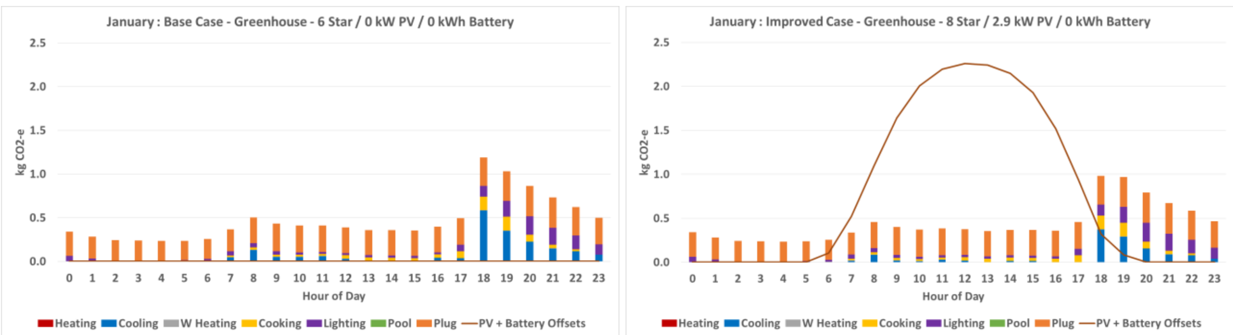

Figure 3: Daily greenhouse gas emissions profile of base and improved new house, January average

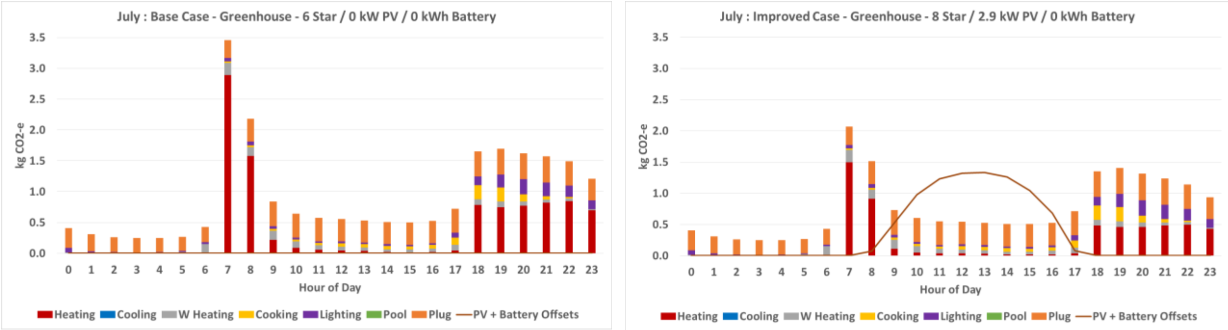

Figure 4: Daily greenhouse gas emission profile of base and improved new house, July average

In addition to modelling a reference case for the new improved house, we modelled a range of variations (or sensitivities), whereby one of the modelling parameters was changed relative to the reference house, and the size of the rooftop PV system was adjusted to just achieve a ZNC status. (Note that in some cases ZNC was slightly exceeded, with the results ranging from 100 to 102%.) The results of this analysis are provided in Table 3.

Table 3. Sensitivity modelling results for new improved house.

Scenarios modelled	PV (kW)	Annual saving		Present value, 40 years, 3% discount			
		Bill ($/yr)	GHG (T/yr)	Costs ($)	Benefits ($)	NPV ($)	BCR
Reference improved house - new	**2.9**	**$708**	**5.76**	**$12,862**	**$18,002**	**$5,140**	**1.40**
House size							
Small	2.6	$610	4.99	$11,383	$15,491	$4,108	1.36
Large	3.1	$797	6.34	$15,351	$20,256	$4,905	1.32
Climate							
Ballarat	2.9	$808	6.47	$12,770	$20,523	$7,753	1.61
Mildura	2.2	$662	5.40	$12,527	$16,823	$4,296	1.34
No. of occupants							
2 people	2.7	$683	5.42	$12,430	$17,358	$4,928	1.40
4 people	3.0	$725	5.93	$13,077	$18,432	$5,355	1.41
5 people	3.2	$750	6.27	$13,507	$19,055	$5,548	1.41
All day occupancy profile	2.9	$750	5.86	$12,862	$19,048	$6,186	1.48
Building shell							
6 Star	3.3	$506	5.61	$9,955	$12,851	$2,896	1.29
7 Star	3.2	$591	5.77	$11,232	$15,017	$3,785	1.34
Appliances							
Best in class efficiency	2.2	$858	5.66	$21,882	$21,810	-$72	1.00
Mixed elec-gas (base) to all elec (improved)	3.9	$697	5.67	$32,520	$17,705	-$14,815	0.54
All elec (base) to all elec (improved)	3.9	$907	7.58	$14,970	$23,050	$8,080	1.54
Swimming pool pump & solar heating	4.2	$971	7.97	$15,567	$24,679	$9,112	1.59
Battery storage							
6 kWh system	3.0	$982	5.65	$26,740	$24,954	-$1,786	0.93
10 kWh system	3.0	$1,015	5.61	$35,226	$25,791	-$9,435	0.73

4.2. Detailed results for the existing Victorian house

The base existing house modelled had estimated annual greenhouse gas emissions of 11.25 tonnes $CO_{2\text{-}e}$/yr, and annual energy costs of $2,841/yr, due to electricity consumption of 4,139 kWh/yr and gas consumption of 109,154 MJ/yr. The main greenhouse gas emission output charts from the tool are shown in Figure 5 for the reference upgrade scenario. Due to the low efficiency of the building shell of the existing base house, it can be seen that winter greenhouse gas emissions (and energy consumption) are much higher than for the new base house (Figure 2). It is also evident that upgrading the building shell efficiency from a 2 Star to a 5 Star rating has a significant impact on reducing greenhouse gas emissions prior to the offsets provided by the rooftop PV system. SV's previous work in this area found that a comprehensive building shell upgrade for existing (pre-2005) houses can achieve an average 5 Star rating, although the upgrade costs are relatively high. Further, it was found that upgrading to the 5 Star level of efficiency is not practical for around 40% of the existing housing stock [4].

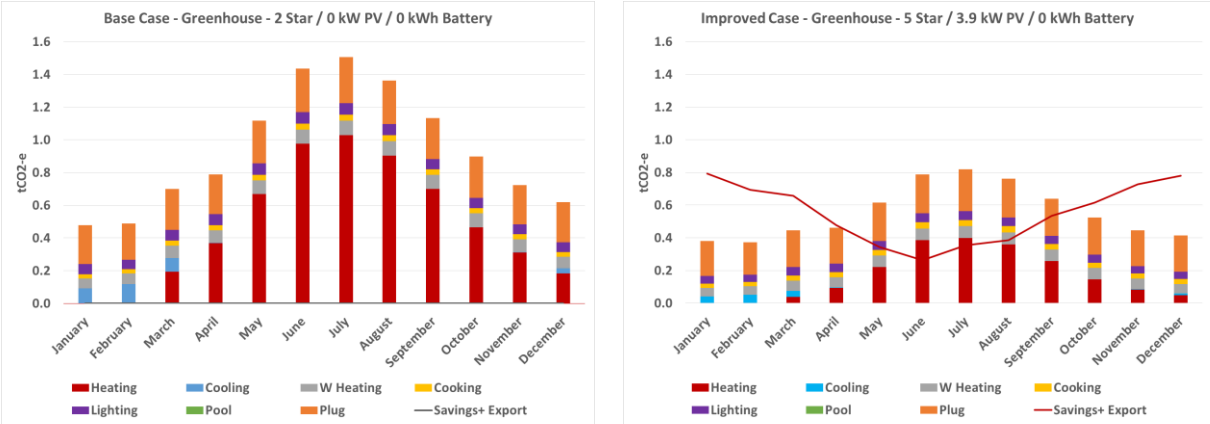

Figure 5: Greenhouse gas emissions from base and improved existing house, by month of the year

Figures 6 (January) and 7 (July) provide examples of the average daily profile data available from the tool for each month of the year, based on greenhouse gas emissions for the existing house. As with the new house, these highlight the large difference between summer and winter emissions, and the mismatch between the profile of the greenhouse offset provided by the rooftop PV and the emissions resulting from the energy end-uses. This mismatch is reflected in the output of the PVs and the household electricity demand, resulting in a high level of export (and a relatively low level of return).

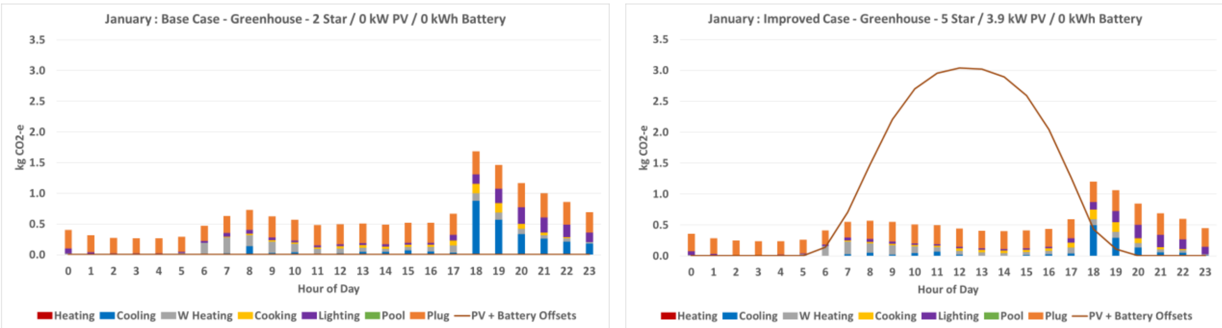

Figure 6: Daily greenhouse gas emissions profile of base and improved existing house, January average

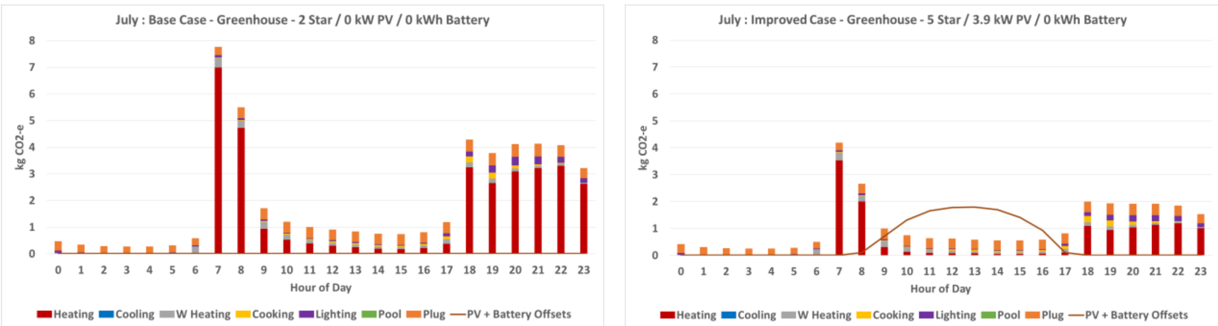

Figure 7: Daily greenhouse gas emission profile of base and improved existing house, July average

In addition to modelling a reference case for the existing house, we modelled a range of variations whereby one of the modelling parameters was changed relative to the reference improved house, and the size of the rooftop PV system was adjusted to just achieve a ZNC status. The results of this analysis are shown in Table 4 below.

4.3. Learnings from the sensitivity modelling

Modelling of the new and existing Victorian houses has shown that, while easier for new houses, attaining ZNC status is practically achievable. It requires that only a fairly modestly sized PV system be installed, provided this is undertaken in combination with building shell and/or lighting and appliance upgrades. For the new house modelled the PV requirement was typically in the range of 2.5 to 4 kW, and for the existing house this was typically in the range of 3.5 to 6 kW. Over the longer term (40 years) most of the upgrade scenarios modelled had a positive benefit-cost ratio. The reducing costs of PVs and increasing energy costs are one reason for this.

Table 4. Sensitivity modelling results for existing improved house.

Scenarios modelled	PV (kW)	Annual saving		Present value, 40 years, 3% discount			
		Bill ($/yr)	GHG (T/yr)	Costs ($)	Benefits ($)	NPV ($)	BCR
Reference improved house - existing	**3.9**	**$1,673**	**11.20**	**$31,929**	**$42,510**	**$10,581**	**1.33**
House size							
Small	3.4	$1,300	8.9	$23,387	$33,026	$9,639	1.41
Large	4.4	$1,857	12.71	$40,534	$47,193	$6,659	1.16
Climate							
Ballarat	4.2	$1,913	13.28	$32,526	$48,598	$16,072	1.49
Mildura	3.0	$1,496	10.12	$29,685	$38,009	$8,324	1.28
No. of occupants							
2 people	3.7	$1,656	10.86	$30,820	$42,070	$11,250	1.37
4 people	4.2	$1,698	11.71	$33,464	$43,152	$9,688	1.29
5 people	4.4	$1,716	12.04	$34,939	$43,610	$8,671	1.25
All day occupancy profile	4.1	$1,874	12.22	$32,329	$47,609	$15,280	1.47
Building shell							
2 Star	5.8	$1,064	11.35	$19,509	$27,030	$7,521	1.39
Appliances							
Stock average efficiency	4.5	$1,496	11.23	$28,221	$38,026	$9,805	1.35
High efficiency	3.1	$1,906	11.30	$40,767	$48,435	$7,668	1.19
Mixed elec-gas (base) to all elec (improved)	4.8	$1,890	11.34	$59,188	$48,035	-$11,153	0.81
All elec (base) to all elec (improved)	4.8	$2,477	15.88	$43,284	$62,938	$19,654	1.45
Swimming pool pump & solar heating	5.3	$2,227	14.87	$34,940	$56,590	$21,650	1.62
100% GreenPower electricity	2.4	$1,375	11.25	$28,746	$34,944	$6,198	1.22
Battery storage							
6 kWh system	4.1	$1,983	11.22	$45,992	$50,377	$4,385	1.10
10 kWh system	4.2	$2,044	11.33	$54,674	$51,943	-$2,731	0.95

As expected, the size of the PV system required to achieve ZNC status increased with increasing house size and number of house occupants, and with decreasing building shell and appliance efficiency. In general, the size was larger in the colder climates – although in new houses the relatively high efficiency of the thermal performance minimum standards seems to mitigate this to some extent. The presence of a swimming pool was found to significantly increase the size of system required.

The results show that the cost-effectiveness of the upgrades required to achieve ZNC status is a fairly complex issue. In general, the building shell and appliance upgrades were more cost-effective (higher BCR) than the PV panels, although this was not the case with the 'best in class' appliances, which may have premium pricing. The cost effectiveness was highest where the output profile of the PVs was more closely matched with the electricity consumption profile of the house (e.g. swimming pool, all electric house, low shell efficiency, 'all day' occupancy profile). The addition of battery storage slightly increases the size of the PV system required, due to the losses in the battery and, even though this increased the energy bill savings by shifting the timing of PV electricity use to more closely match the usage profile, it significantly reduced the cost effectiveness of the upgrade to ZNC status. This was due to the current high cost of battery storage systems, although these costs are expected to reduce significantly over the next five or so years.

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