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Post-occupancy energy consumption of BASIX affected dwellings in the Sydney metropolitan area

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Abstract

Australian residential sector contributes approximately 13 per cent of the total greenhouse gas (GHG) emissions. The New South Wales (NSW) government in Australia has introduced mandatory energy efficiency/ GHG emissions reduction target through the Building Sustainability Index (BASIX) assessment tool, which estimates the operational energy consumption and GHG emissions from new residential developments based on information available at the building design stage. However, post-occupancy energy consumption can be different from the estimated figures at the design stage. This research aims to disentangle the relationships between various attributes that influence energy consumption at the dwelling scale through a post-occupancy residential energy performance analysis model. The model combines multidimensional attributes which include building design features, construction quality, possession of household appliances and their usage, demographic and homeowners' energy use behaviour. The model allows comparing the estimated energy consumption/ GHG emissions from BASIX assessment with actual energy consumption/ GHG emissions in the real household environment. Data for this study has been collected from a sample of 48 BASIX affected dwellings located in the greater Sydney area which includes energy bill data, real-time monitoring of electricity consumption and indoor environment (temperature and humidity) data. This paper reports findings based on the data collected from late 2015 to mid-2016 from 16 dwellings. The initial results demonstrate discrepancies in energy consumption (therefore GHG emissions), household occupancy and breakdown of energy consumption for various services between BASIX estimates and the collected data. Given that BASIX assessment is based on information available at the design stage, the reported discrepancies are expected. More importantly, the initial results show that BASIX assessments under-estimated energy consumption for active cooling and over-estimated consumption for lighting and ventilation and other household plug loads.

Keywords: BASIX; Post-occupancy energy performance; household energy; GHG emissions

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1. Introduction

Advanced nations' per capita residential energy consumption is relatively high compared to developing countries [1]. In the context of global climate change, advanced nations have greater responsibilities to explore avenues to reduce their energy consumption and therefore curtail greenhouse gas (GHG) emissions. The Intergovernmental Panel on Climate Change [2] recommends various cost effective measures to reduce GHG emissions from new and existing buildings such as reducing energy consumption and embodied energy in buildings, promoting low carbon fuels and the use of renewable energy sources.

Australian Commonwealth and State Governments have adopted various measures that aim to reduce energy consumption and GHG emissions in the residential sector. Minimum requirements of building shell thermal performance were introduced in the Building Code of Australia (BCA) for houses in 2003 and for unit apartment buildings in 2005. Since 2004, the New South Wales (NSW) Department of Planning and Environment (DP&E) has introduced the Building Sustainability Index (BASIX) that requires new residential buildings to meet their mandatory reduction targets of water consumption and energy consumption (expressed in GHG emissions) before their development can be approved. BASIX includes an assessment tool that estimates the water consumption and GHG emissions from a proposed residential development based on information available at the design stage. By comparing the estimated values with the benchmark water consumption of 90,340 litres/person/year and benchmark GHG emissions of 3,292 kg of CO_2^{-e}/person/year from an average home in NSW in 2002/03, BASIX requires all new dwellings to achieve reduction target by up to 40% from the benchmarks [3, 4].

In addition to water consumption and GHG emissions, BASIX sets minimum requirements of the building shell thermal performance in accordance to the Nationwide Energy Rating Scheme (NatHERS) administered by the Australian federal government [5].

This paper focuses on the energy performance of BASIX affected dwellings after they are built and occupied. The paper presents a post-occupancy residential energy performance analysis model which facilitates comparing the energy consumption and GHG emissions between the estimates from the BASIX assessment tool and the actual energy consumption from a number of monitored dwellings to identify any discrepancies and factors contributing to the discrepancies.

2. Performance monitoring of energy consumption and GHG emissions from BASIX affected dwellings

Many researchers hailed the initiation of NSW government to implement BASIX as an effective environmental planning policy [6-9]. More than 450,000 dwellings have been approved for construction in NSW since the introduction of BASIX in 2004 [10]. BASIX enables rainwater tanks to become one of the common building features, and plays a pivotal role to phase out inefficient electric hot water systems in new residential developments [11]. A cost-and-benefit analysis commissioned by DP&E in 2009 found that dwellings complaint with BASIX requirements generate a positive benefit to NSW through lower water and energy consumption, GHG emission reductions and avoided electricity network augmentation [12]. It is estimated that reductions in water and energy consumptions will save the affected households A$495 million in water bills and A$1,800 million in energy bills by 2050 [4].

To further evaluate the effectiveness of BASIX, DP&E has been working with water and energy utilities to monitor the water and energy consumption of BASIX affected dwellings after occupation. A previous study from Energy Australia, one of the electricity utilities for the Sydney metropolitan area, found that less than 40% of a sample of around 1,000 BASIX affected dwellings are able to achieve their mandatory GHG emissions targets after occupation [13]. On average, GHG emissions from the sampled households are only 16% lower than their respective benchmarks, as compared to the mandatory targets of 40% from the benchmarks applicable to the Sydney metropolitan area.

Given that BASIX as an environmental planning policy only covers built-in features of proposed dwellings at the design stage, a certain degree of discrepancies with GHG emissions after occupation is expected. Since the Energy Australia study was based on quarterly electricity billing data, the lack of actual number of occupants in the sampled dwellings and the breakdown of consumption data does not allow further investigation into the pattern of energy consumption from various services such as hot water, active heating, active cooling, lighting, pool and spa and other plug loads. Gas consumption from the sampled dwellings was not accounted for. Landreth et al. [4] outlined a number of limitations and recommended further research on the specific areas which may help in understanding discrepancy between estimated and actual GHG emissions from BASIX affected dwellings and these include:

- Confirming BASIX compliance commitments made at the design stage
- Understanding differences of BASIX assumptions in dwelling occupancy (based on number of bedrooms) and current user behaviour patterns
- Better accommodating for electricity consumption from plug-in appliances in the BASIX tool

The above recommendations indicate the need of a more comprehensive post-occupancy evaluation to unravel energy consumption by combining building attributes, household demographic profile, inventory of plug-in appliances and household energy use behaviour. This paper discusses the post-occupancy energy performance analysis model developed under the Cooperative Research Centre for Low Carbon Living (CRC-LCL) BASIX project. The project aims to compare actual energy consumption (or GHG emissions) from a number of BASIX affected dwellings with the estimated consumption from the BASIX assessment tool, and identifies potential factors (both within and beyond the remit of BASIX as an environmental planning policy) that affect household energy consumption.

Findings of the CRC-LCL BASIX project will assist to identify areas for improvement of the BASIX assessment tool, establish the links between government regulations, design options and post-occupancy behaviour and inform future sustainability strategies and policy.

3. Post-occupancy Energy Performance Evaluation (PoEPE) model

The PoEPE model (Fig. 1) has been developed to compare actual energy consumption (and GHG emissions) from a sample of BASIX affected dwellings with the estimated consumption from the BASIX assessment tool, and to further investigate the discrepancies identified (if any) by exploring various factors related to household energy consumption. Circuit level electricity consumption data allows comparing breakdown scenarios of the actual energy consumption with the BASIX breakdown estimates. Further, breakdown of energy consumption from various services can also be used to identify the influential factor(s) and their contribution to household energy consumption.

The model has two major components – BASIX estimated energy consumption and GHG emissions, the actual household energy consumption and GHG emissions, and other relevant information such as, household characteristics and building features, households' energy use behavior, indoor environmental conditions and energy sources to further identify influential factors and their contribution in energy consumption.

a) BASIX estimated energy consumption and GHG emissions – The BASIX tool estimates yearly household energy consumption and corresponding GHG emissions. The consumption breakdown from various built-in energy services (namely hot water, ventilation, active cooling, active heating, lighting, pool and spa and alternative energy supply) and other end uses such as cooking and whitegoods were obtained from DP&E. Energy consumption is estimated by BASIX based on information of the proposed dwelling provided by designers or architects as they try to achieve the BASIX mandatory reduction targets of GHG emissions as part of the development approval. The BASIX estimate also depends on a number of default variables (such as household occupancy as informed by the Australian Census data) that vary with dwelling type and geographic location.
b) Actual household energy consumption and GHG emissions – Actual energy consumption is determined at two stages. In the first stage, utility bill data (both electricity and gas) was collected from the participating dwellings and in the second stage, circuit level monitoring system was installed to collect a full year of real-time energy consumption from various services and end uses.
c) Other relevant information – Energy consumption within household level is instigated by multiple factors which are related with building, occupants and energy source. Building design, construction and indoor environmental condition will contribute energy consumption for maintaining comfortable indoor environment [14-16]. Similarly, occupants' characteristics, i.e. socio-economic status, energy use behavior, number of occupants, household income and house occupancy pattern are some of the important variables that influence overall household energy consumption [1, 16-21]. Availability of energy sources can have an impact on energy

consumption and GHG emissions since the GHG intensity of reticulated gas is lower than grid electricity in Australia [22].

Fig. 1 illustrates PoEPE model which combines the multi-dimensional attributes related with household level energy consumption. These attributes are investigated to understand their implications to actual energy consumption and discrepancy with the BASIX estimates (if any).

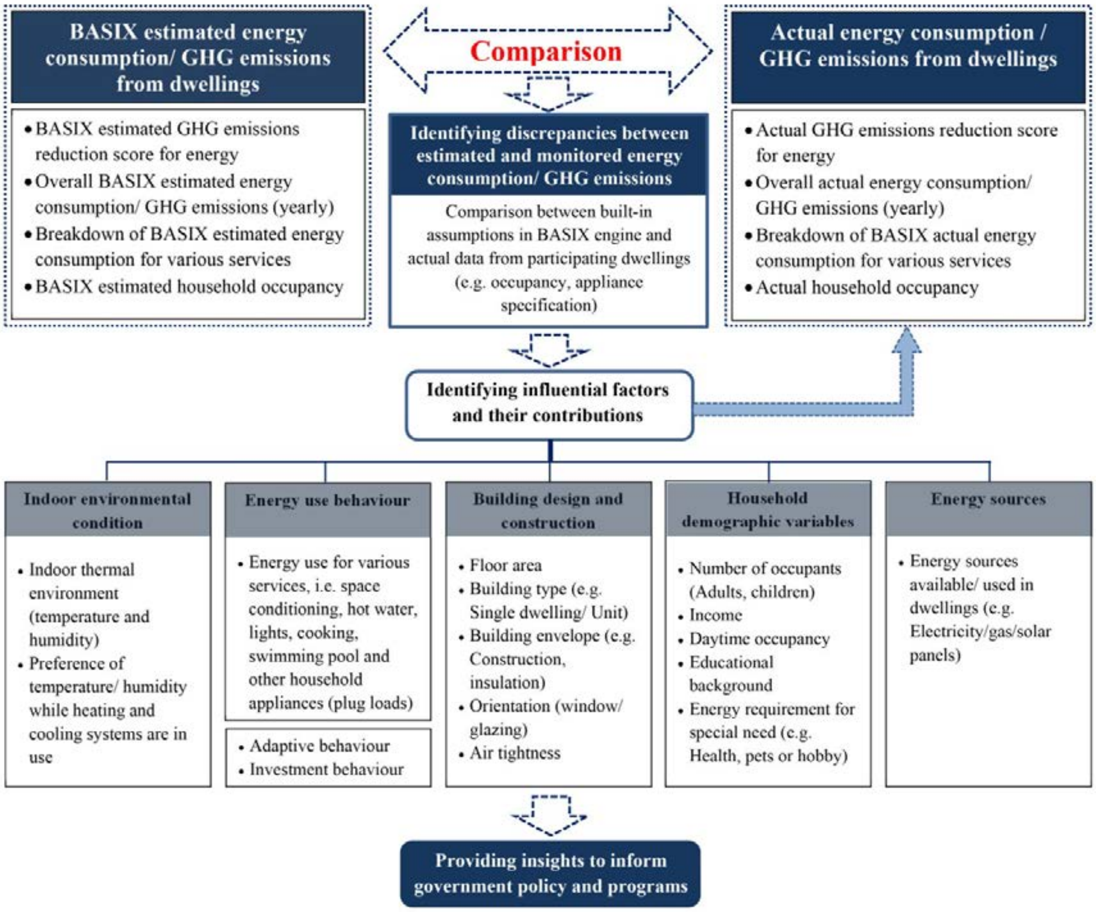

Fig. 1. Post-occupancy energy performance assessment model to compare BASIX estimated and actual energy consumption / GHG emissions from NSW dwellings

In the context of the PoEPE model, this paper reports preliminary results from the participating dwellings and analyses post-occupancy energy performance of BASIX affected dwellings. It further compares:

a) actual yearly energy consumption (and GHG emissions) and the BASIX estimates
b) actual monitored energy consumption for various services and end usage, and the BASIX estimated breakdown of energy consumption
c) actual household occupancy and BASIX estimated household occupancy
d) the relationship between outdoor/ indoor temperature and corresponding energy consumption for cooling
e) the relationship between energy consumption versus floor area and occupancy profile

4. Participants recruitment, data collection and real-time energy and indoor environmental monitoring

The CRC-LCL BASIX project adopted a two-stage recruitment process. The initial survey collected preliminary information on location of dwellings, building age, availability of energy sources, tentative spending on household energy, use of heating and cooling systems, number of occupants and dwelling occupancy profile. In total, 153 responses were received and 76 of them agreed to participate in the second round of data collection and installation of real-time energy and indoor environmental monitoring system.

By the end of March 2016, a total of 48 BASIX affected dwellings have participated in the project. These dwellings have been recruited since May 2015 from 20 different postcodes within the Sydney Metropolitan Area (Fig. 2). They comprise 35 free-standing houses and 13 apartments. Table 1 summarizes some of the key characteristics of the participating dwellings. Average floor area of the participating dwellings is 177.7 m^2 with 3.5 bedrooms and 2.7 occupants. Seven of the participating dwellings do not have air-conditioners and four of them have outdoor swimming pools.

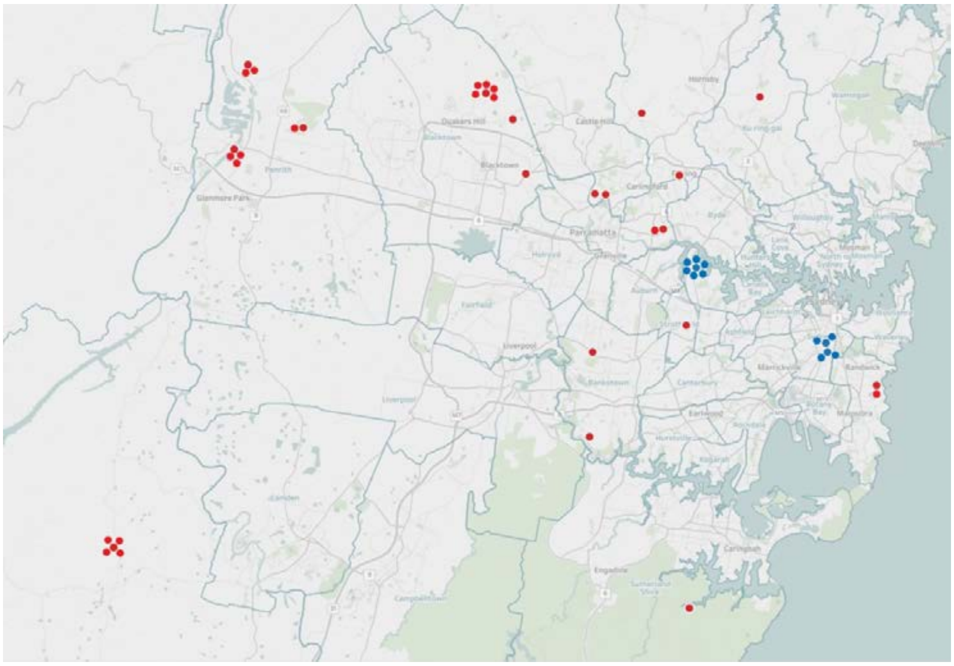

Fig. 2. Location of 48 participating dwellings within Sydney metropolitan area. The red dots represent free-standing houses and blue dots represent apartments

Building data, household demographic data, inventory of home appliances and utility bills (electricity and gas) data have been collected through surveys and during home visits of participating dwellings. In addition, real-time circuit level electricity consumption data and indoor environmental (temperature and humidity) data were collected using electricity monitoring systems and environmental sensors installed between September 2015 and April 2016.

The electricity monitoring system was installed at electrical distribution/ meter box by an accredited electrical contractor. The electrician was accompanied by the researcher to ensure the wiring and metering configuration was consistent with the project requirement. Generally, six circuits were measured from each house which comprised air conditioner, lighting, plug loads, hot water, pool pump, cooktop and oven and generated solar power. The monitoring system records voltage, current and energy consumption by each circuit in every minute and uploads data to an external server at least once a day through a dedicated Wi-Fi hotspot set up specifically for the project. Similarly, temperature and humidity sensors were installed in the living areas and one of the bedrooms. Each sensor records 15 minutes interval data and uploads to the server once in two days. Both electricity monitoring data and temperature and humidity data sets are stored in Structured Query Language (SQL) database for analysis. Monitoring is still on-going at the time of writing and a full year of data is expected to be collected from all the participating dwellings by early 2017.

Table 1. Characteristics of participating dwellings

Particulars	Single storey house	Double storey house	Multi-unit apartment	Total sample
Number of participating dwellings	17	18	13	48
Average floor area (m^2)	188.6	245.8	69.2	177.7
Average number of bedrooms	4.0	4.2	1.7	3.5
Average number of occupants	2.8	3.2	1.8	2.7
Ratio of Bedrooms and occupants	1.4	1.3	0.9	1.3
Average BASIX energy score (% reduction in GHG emissions from benchmark)	42.2	40.6	N/A	-
Number of dwellings with reverse-cycle air-conditioner	16	15	10	41
Swimming pool	2	2	-	4

5. Post-occupancy performance analysis

Based on data collected from late 2015 to mid-2016, this section presents the post-occupancy performance of participating dwellings which covers actual GHG emissions, household occupancy profile, energy consumption profile, indoor environmental condition, and energy consumption versus other building and demographic variables. This paper does not cover in-depth energy use behavior analysis and building diagnostics.

5.1 GHG emissions from the participating dwellings

Fig. 3 shows BASIX estimated GHG emissions at the design stage and post-occupancy GHG emissions from the participating dwellings. Post-occupancy GHG emissions are calculated using energy bill data and the emission intensity factors of grid electricity and gas used in the BASIX assessment tool. As billing data from gas utility is not available to all participating dwellings at the time of writing, only 22 of the 48 participating dwellings have the complete BASIX-estimated and post-occupancy GHG emissions data available as shown in Fig. 3.

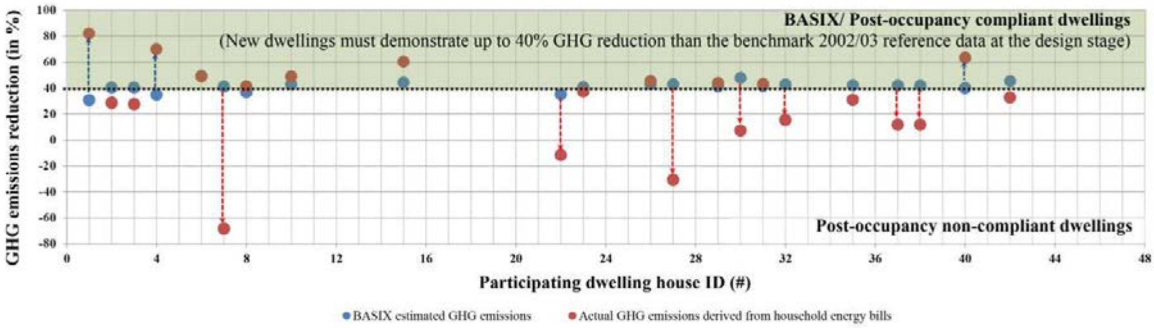

Fig. 3. Comparison of BASIX estimated GHG emissions reduction and post-occupancy GHG reduction from participating free-standing houses [BASIX estimation and post-occupancy GHG emissions reduction for three dwellings (#6, #29 and #31) are overlapping]

All of the 22 participating dwellings are free-standing houses with a BASIX mandatory GHG reduction target of 40%. The preliminary investigation identifies both high performing dwellings (indicated by blue upward arrows) where actual GHG reductions are higher than BASIX estimates, as well as low performing dwellings (indicated by red downward arrows) where actual GHG reductions are lower than those estimated by BASIX. Two dwellings (#1 and #4) demonstrated a significant GHG emissions reduction of up to 80% from the 2002/3 benchmark. On the other hand, seven dwellings' (#7, #22, #27, #30, #32, #37 and #38) GHG emissions reduction was less than the 40% target with an average of -9%. The negative GHG emissions reduction figure infers to higher emissions than the benchmark level. Three of the dwellings (#7, #22 and #27) consumed significantly high energy and therefore high GHG emissions than the benchmark level.

5.2 Occupancy profile in the participating dwellings

As BASIX is applicable to new residential dwellings at the stage of development approval, discrepancies are expected between BASIX assumed occupancy profile and the actual occupancy from individual participating dwellings. Difference in occupancy is one of the major factors behind the discrepancies of GHG reduction found in Fig. 3 because household energy consumption (and hence GHG emissions) is shown to be highly sensitive to the number of occupants [23]. Fig. 4 shows that the highest level of discrepancy in terms of occupancy is found in single storey houses (Average=1.33; Extremes=+3.15/ -2.44), followed by double storey houses (Average=0.83; Extremes=+2.15/ -2.44) and then in apartments (Average=0.64; Extremes=+1.03/ -0.97). The positive sign indicates higher level of occupancy assumed by BASIX tool and negative sign informs higher number of occupants at post-occupancy stage.

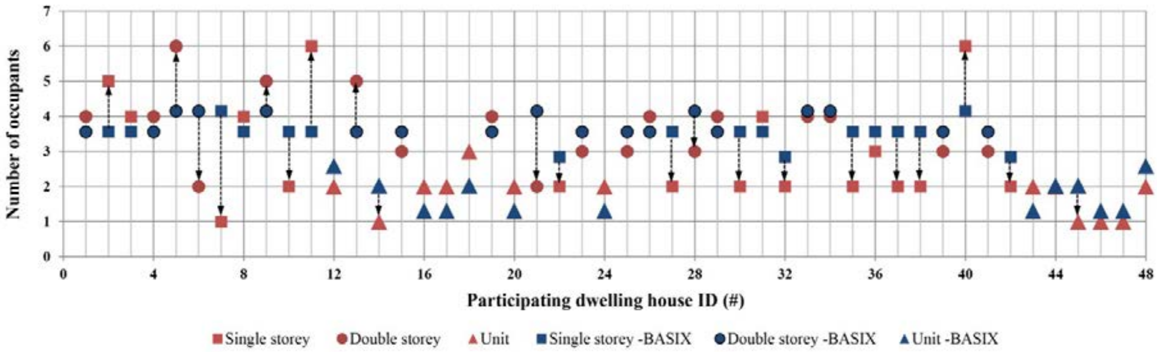

Fig. 4. Comparing BASIX assumed household occupancy and post-occupancy occupancy profile from participating dwelling

5.3 Post-occupancy energy consumption profile during 2015/6 warm season and until mid-2016

Installation of the monitoring systems started in early September 2015. The 2015/16 warm season lasted for about six months (October 2015 to March 2016). In early October 2015, Sydney metropolitan area experienced daily maximum temperature exceeding 30^0C for around eight days. Similarly, March 2016 was also unusually warm with half of the month's daily maximum temperature above 30^0C. Therefore, the period from October 2015 to March 2016 is considered as the warm season for further analyzing the monitored electricity data and comparing it with the cooling energy consumption estimated by BASIX. Since the research is ongoing at the time of writing, monitored data from the nine months between October 2015 and June 2016 is used for predicting yearly energy consumption for lighting and ventilation and plug loads.

Altogether 16 participating dwellings (10 free-standing houses and 6 apartments) had the energy breakdown data covering the warm season cooling data and the period between October 2015 and June 2016 for the other end uses. Fig. 5 compares the energy consumption between the BASIX estimates and the post-occupancy monitored data.

Generally, most of the dwellings consumed significantly higher energy for cooling with an average of 6 times (lowest, 1 and highest, 31); houses #15, #27 and #2 in particular demonstrated the highest level of discrepancy with their actual energy consumption being 31, 13 and 6 times higher than the BASIX estimates respectively. On the other hand, energy consumption for lighting and ventilation and plug loads are generally over-estimated by the BASIX tool. For lighting and ventilation, BASIX estimated on average by 5 times (lowest, <1 and highest, 17) more energy consumption than the sample dwelling consumed and BASIX estimation for plug loads was on average 2 time (lowest, 1 and highest, 4) higher than the post-occupancy monitored energy consumption.

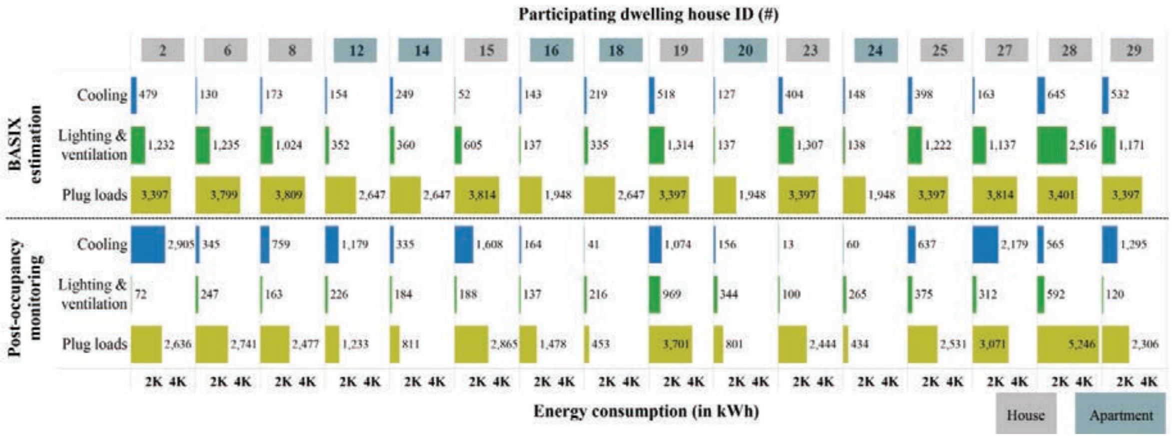

Fig. 5. Comparing BASIX estimated and post-occupancy energy consumption data for cooling, lighting & ventilation and plug loads

Fig. 6 illustrates the monitored monthly energy consumption from cooling, lighting and ventilation, and plug loads from the same 16 participating dwellings. Overall, energy consumption in free-standing houses is higher than that of apartments; particularly, for plug loads and cooling energy consumption. Interestingly, the pattern of energy consumption is consistent throughout the warm season for every dwelling; the dwellings that consumed overall high cooling energy (#7, #15 and #27) used high energy for cooling throughout the warm season. The highest level cooling energy was used in February with an average of 264kWh for free-standing houses and 89kWh for apartments.

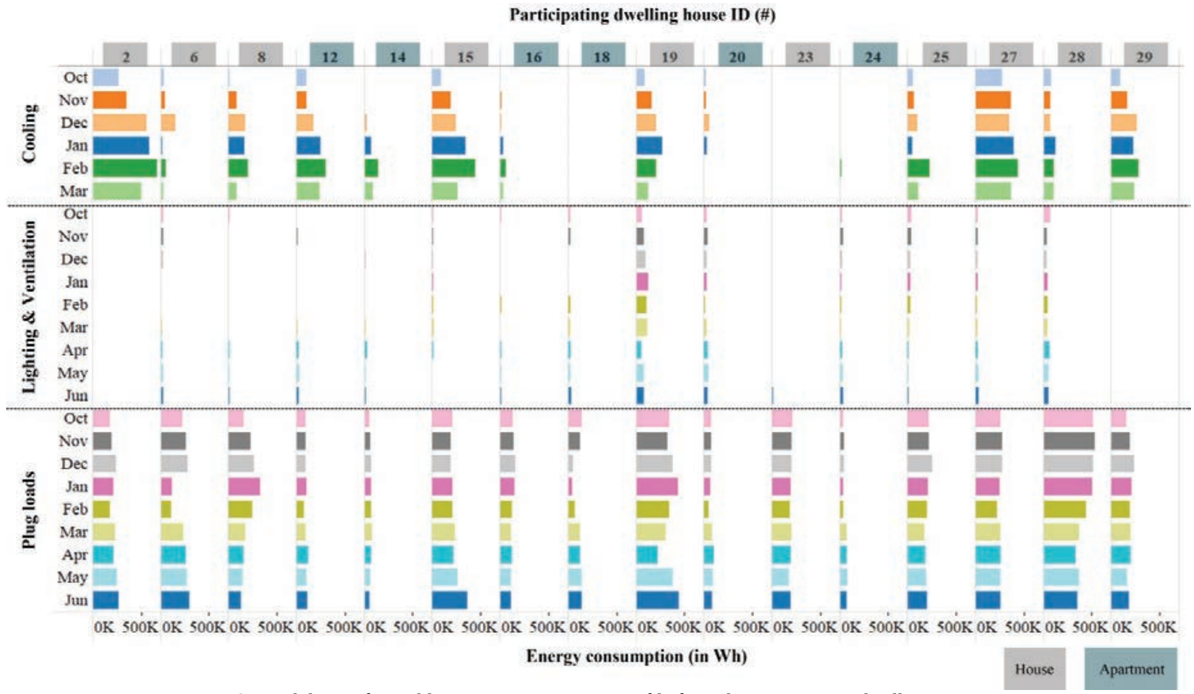

Fig. 6. Breakdown of monthly energy consumption profile from the participating dwellings

5.4 Outdoor temperature and use of air-conditioner

Outdoor environmental conditions influence the indoor environment. Most often, households cooling energy consumption increase to cool the buildings in a hot summer day. A warm week on February (10^{th} – 17^{th}) is selected to understand the usage of air-conditioning and corresponding energy consumption from participating dwellings. Early on the week, maximum temperature was around 30^0C with diurnal temperate ranging around 10K. On 14^{th} February, Sydney experienced a heat wave with maximum temperature of 37.9^0C. Later in the week, temperature dropped due to low pressure system and maximum temperature hovered around 25^0C. Fig. 7 illustrates daily energy consumption from the participating dwellings. Dwellings #2, #8, #12 and #15 used air-conditioner for cooling regularly on hot days. It was noted that most of the dwellings used high amount of energy on the heatwave day (14^{th} Feb) and the next day (15^{th} Feb) when the diurnal temperature range was around 6K (minimum, 22.7^0C and maximum, 30.1^0C) with an average 26.4^0C. The relatively high average temperature due to high minimum temperature prevented natural cooling of thermal mass and therefore high usage of air-conditioning to cool down building for maintaining thermal comfort.

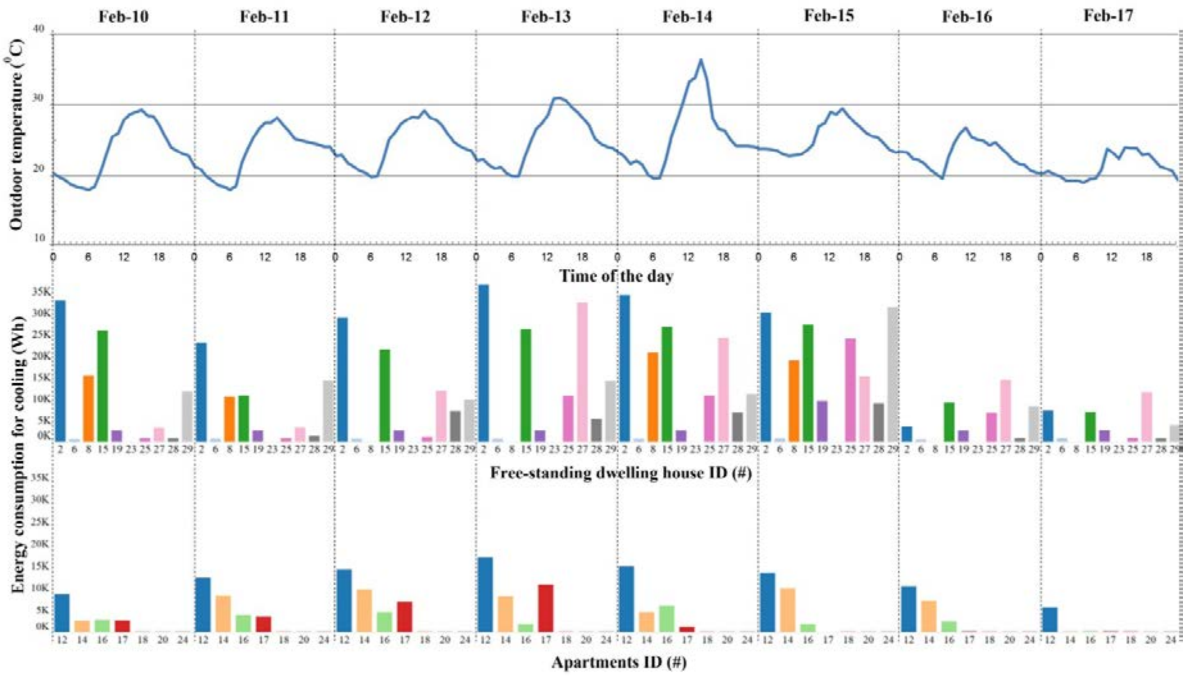

Fig. 7. Impact of outdoor temperature on energy consumption for cooling (by air-conditioners) in a warm summer week

5.5 Indoor temperature profile and corresponding energy consumption

In most of the participating dwellings cooling is done by ducted air-conditioners. Fig. 8 illustrates outdoor/ indoor temperature profile and use of air-conditioner to maintain the desired indoor temperature profile from a participating dwelling (#2) which consumed the highest cooling energy in the last warm season. This dwelling has demonstrated a significant (6 times) discrepancy for cooling energy consumption between BASIX estimates and actual energy consumption. In February, this dwelling consumed 662kWh of energy for cooling. The average indoor maximum and minimum temperature were maintained within a 2K band (24^0C to 25.8^0C) on February which is indicated by dotted lines in Fig. 8.

On February 25 2016, Sydney experienced another heat wave with maximum temperature of 40.3^0C in Sydney Olympic Park weather station. This single storey house maintained an average temperature of 25.0^0C with only 1K temperature variation. The air-conditioner was used for around 14 hours (8:30 AM to 11 PM), which consumed 56.70kWh of energy on that day. Another participating dwelling from the nearby suburb used cooling only for 3 hours in the evening on that day and used about a quarter of the energy than the previous dwelling (#2).

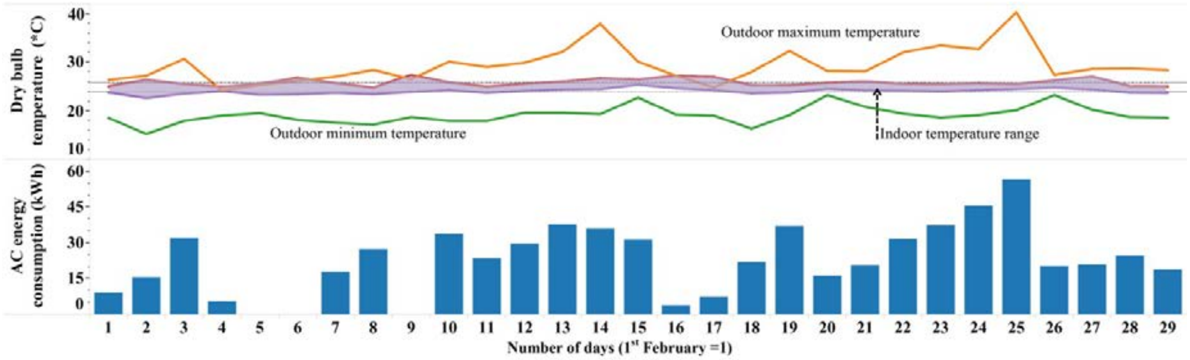

Fig. 8. Indoor, outdoor temperature and corresponding AC energy consumption for maintaining thermal comfort in a dwelling (#2) in February.

5.6 Energy consumption versus floor area and occupancy profile

Scatter plots of breakdown of energy consumption against building floor area and occupancy profile were carried out to see if any relationship can be established through them. Building floor area showed strong correlation with BASIX estimated cooling, lighting and ventilation and post-occupancy plug loads energy consumption (Fig. 9). BASIX estimated cooling, and lighting and ventilation energy consumption was found to increase with floor area. However, this trend was not significant with the post-occupancy monitored data for those variables. Post-occupancy plug loads energy consumption was correlated with the floor area.

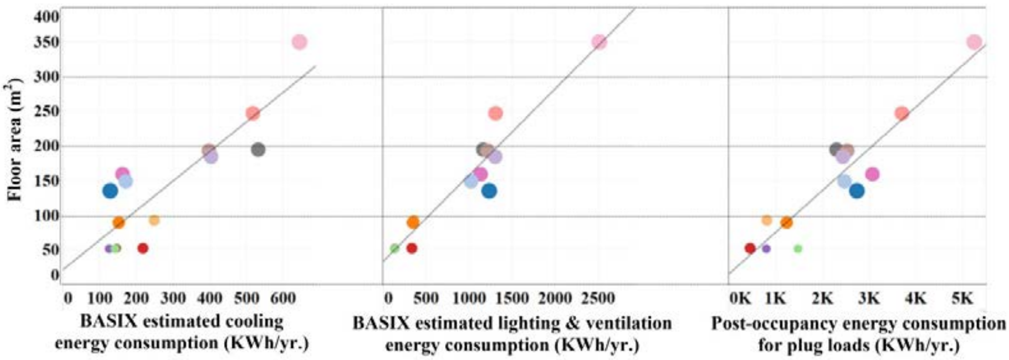

Fig. 9. Relationships between energy consumption for various services and building floor area (the dots represent participating dwellings)

With the available six to nine months' monitored data, occupancy profile did not show strong correlation with either BASIX estimated or post-occupancy energy consumption profiles for the sample population.

6. Discussions and conclusion

This paper presented a post-occupancy energy performance assessment model to evaluate the performance from a sample of BASIX affected dwellings after occupation. The paper compared BASIX estimated GHG emissions, household occupancy profile, breakdown energy consumption scenario with post-occupancy survey data, energy bill data and real-time energy and indoor environmental monitoring data. This paper also reported some of the findings from a subset of participating dwellings.

Given that BASIX is applicable to residential dwellings at the stage of development approval, discrepancies of energy consumption between the post-occupancy data and the BASIX estimates are expected. When the number of occupants in a dwelling is not considered, discrepancy between BASIX estimated and post-occupancy GHG emissions were noticed in around two-third (14 dwellings) of the valid sample. The post-occupancy GHG emissions was on an average 13% less than the BASIX estimation. However, when the GHG emissions was calculated using actual occupancy profile, slightly more than half of the participating dwellings' GHG emissions were higher than the required threshold of 3,292 kg of CO_2^{-e}/person/year. This is due to the lower number of occupants than the BASIX estimation at post-occupancy energy calculations.

BASIX estimates dwelling occupancy from the Australian Bureau of Statistics' Census data, based on location, dwelling type and number of bedrooms. Two of the participating dwellings have higher actual occupancy than the BASIX estimates, 13 have lower actual occupancy and 7 have no difference. It is noted that actual GHG emissions of the dwellings with low occupancy were reduced by around 20% than that of BASIX estimated; but when it was calculated per capita, 11 out of 13 dwellings exceeded the benchmark GHG emissions threshold. On average, there was 15% over-estimation on GHG emissions by the BASIX for the dwellings with no difference in occupancy. However, 6 out of 7 dwellings' per capital GHG emissions were within the mandatory GHG emissions threshold.

The results presented in this paper confirmed the discrepancy in aggregate as well as for breakdown scenarios, they show that the BASIX can both under-estimate and over-estimate the energy consumption by the individual systems or at end uses. In 12 out of 16 dwellings, BASIX tool under-estimated cooling energy consumption by 6 times on an average, whereas in most of the sample dwellings BASIX over-estimated energy consumption for lighting and ventilation, and plug loads by on an average 5 times and 2 times respectively. Since the sample size was small (only 16 households), it was not possible to demonstrate the statistical significance of one item against the other. Generally, higher outdoor daily average temperature triggered high energy consumption for cooling. Outdoor ambient temperature, indoor temperature and daily energy consumption for cooling highlighted energy consumption trend in a dwelling. It also means that higher occupancy during daytime increases the use of cooling energy and ultimately the total energy consumption.

Since the major discrepancy between BASIX estimation and monitored data is observed in cooling energy consumption, which is often independent of the number of occupants given that only two (daytime and night-time) zones ducted air-conditioning systems are installed in majority of the participating dwellings. Generally, if the design of the buildings and construction quality is similar, larger floor area corresponds to greater energy requirement for heating or cooling the building. A detailed analysis incorporating building design attributes, behavior relating to use of air conditioners and dwelling occupancy periods will further help to identify the factor(s) that has major influence in cooling energy consumption.

This study did not find a strong correlation between dwelling occupancy profile and energy consumption at aggregate or breakdown scenarios for various services and end usages. However, building floor area exhibited a strong correlation with post-occupancy plug loads energy consumption, BASIX estimated cooling, and lighting and ventilation energy consumption.

This paper sourced six to nine months of monitored data and tested the post-occupancy energy performance assessment model to compare BASIX estimated energy use and GHG emissions with actual energy consumption from the BASIX affected dwellings. Discrepancy between the two data sets are outlined; however, further analysis needs to be carried out by collating additional data from the participating dwellings, combining energy use behavior, building design attributes and building diagnostics information to unravel the major influential factors in household energy consumption.

Acknowledgements

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