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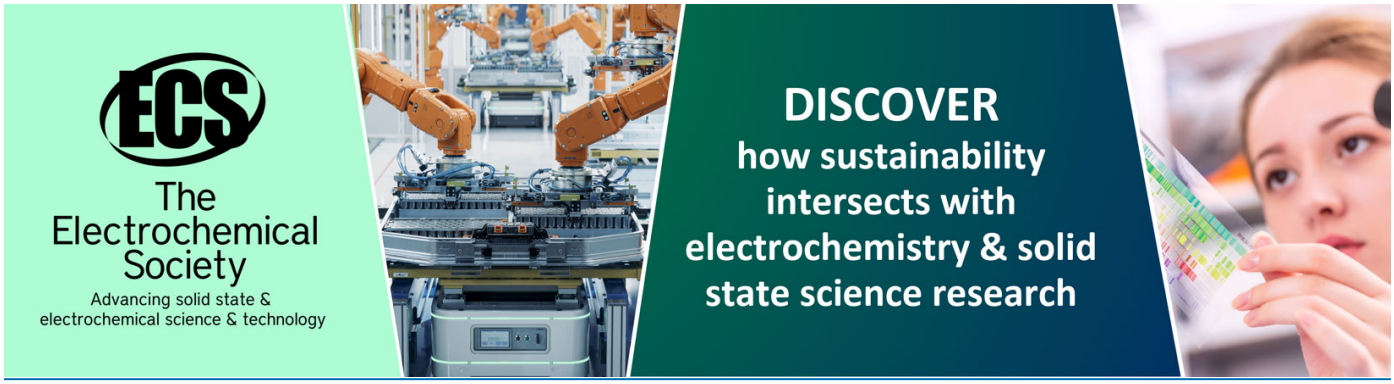

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An extensive study on the relationship between energy use, indoor thermal comfort, and health in social housing: the case of the New South Wales, Australia

S Haddad[1,*], G Pignatta[1], R Paolini[1], A Synnefa[1] and M Santamouris[1,2]

[1] Faculty of Built Environment, University of New South Wales, Sydney, Australia
[2] Anita Lawrence Chair High Performance Architecture
[*] s.haddad@unsw.edu.au

Abstract. Over three million people live below the poverty line in Australia. Low-income households suffer from overheated or cold homes and experience problems associated with energy inefficiency and poor indoor environmental quality (IEQ), which ultimately affect residents' quality of life, comfort, well-being, physical and mental health. These circumstances are the main drivers of a social challenge known as Energy Poverty (EP) when residents have difficulties in paying the electricity bills. EP needs to be addressed by i) implementing energy efficiency measures in social housing, ii) educating low-income families about energy saving practices and behaviours, iii) developing new energy policies. We investigated the level of EP in social housing located in New South Wales, Australia. Indoor thermal environment and air quality were monitored in 106 low-income households over the winter and summer periods 2018/2019. Questionnaire responses informed the real living conditions of participating families, including their medical history and behaviours concerning energy use. The information presented here will be used to investigate the possible evolution of IEQ and EP as a function of climate change and extreme weather events on housing and suggest countermeasures and target policies to benefit the vulnerable households and alleviating the EP level of the region.

1. Introduction

Housing plays a key role in the living standards of people, affecting residents' health and wellbeing. The absence of affordable, secure, and appropriate housing can have negative social consequences, e.g., homelessness, poor health, and lower rates of employment and education. Energy Poverty (EP) has a serious impact on the quality of life of low-income households, as well as on the social and economic aspects of the community. In Australia, large low-income families, pensioners, and indigenous have been hit by the increase in energy costs and face increasing difficulty in paying electricity and gas bills. Further, climate change, Urban Heat Island (UHI) phenomenon and extreme weather conditions in urban areas have a significant impact on the quality of life, energy use, and health of residents, especially of vulnerable population [1]. Overheating of urban areas is turning into a tremendous problem for Australian cities resulting in the peak UHI intensities of 11°C [2]. The yearly average air temperatures in Australia have increased by 0.9 °C since 1910, and the frequency of extremely hot days has been more than double the frequency of very cold days during the past ten years [3]. Summertime indoor environmental conditions in low-income households lead to thermal discomfort and heat stress, especially during heat waves. Despite the importance of the topic, very little is known about the specific penalties and the impact of extreme weather conditions in Australian low-income population. Additionally, there is little empirical evidence about the indoor air and environmental quality of social housing.

This research aims to assess the living conditions of the low-income population using an integrated approach where health, energy consumption, as well as Indoor Environmental Quality (IEQ)

are considered. The term IEQ is used to characterize the indoor comfort conditions associated with the thermal comfort and health of the building occupants. Factors affecting IEQ are temperature, humidity, air velocity, mean radiant temperature, lighting and acoustic levels, and concentration of indoor pollutant that defines the Indoor Air Quality (IAQ) in a building. Non-satisfactory levels of IEQ may cause health problems and increase the mortality rate. Recent research reinforces that various parameters defining the housing IEQ, ventilation, inadequate insulation, IAQ, the presence of internal condensation, mould, and damp are associated with illnesses like bronchitis, pneumonia, asthma, influenza, heart deceases, arthritis, migraine, as well as social and mental health problems, e.g., depression, anxiety, constraints of mobility and isolation [4]. Therefore, tackling EP and improving the IEQ of low-income housing is of great importance, which can be performed by the following actions: i) reduce energy prices for the households; ii) improve energy efficiency of buildings occupied by vulnerable households including a necessary commitment and effort in educating residents to the rational use of energy; iii) work in the social field by strengthening low-incomes as much as possible. While the reduction of energy prices and social work are beyond the scope of this research, the energy efficiency measures for low-income housing are the challenge of this study, which requires a deep knowledge of the actual conditions of the social housing and the residents.

Currently, the rising cost of energy is of concern to all Australians. Low-income large-family households, most exposed to the concept of EP, live in the struggle-town suburbs of Australian biggest cities [5]. The term EP is used to describe a situation of a household not able to satisfy socially and materially the necessary energy services in the residence [6]. It is a moral and economic issue that has a significant impact on the quality of life of citizens, affects seriously indoor comfort levels in energy-poor houses, influences social attainment, has a negative effect on health, and results in a significant increase of the seasonal mortality and morbidity [1].

EP reduces the capacity of low-income households to live in houses with proper environmental protection and energy installations, decreases their potential to use energy and achieve the required indoor environmental conditions. It has a significant impact on residents' health increasing the excess winter/summer mortality [1]. Numerous studies have shown that low-income population is unable to cover part or the whole of their specific energy needs and, as a result, IEQ does not meet the required levels for comfort and health purposes. Because of the inappropriate housing thermal standards, the low-income population must spend a much higher share of their income to satisfy the household needs compared to the average or high-income population. This study is part of a project designed to deliver the knowledge needed to investigate the impact of climatic conditions on housing characteristics and quality, health, comfort and indoor environmental conditions, and energy penalties related to the low-income population in New South Wales (NSW). This paper investigates the nexus between building design and energy performance, comfort, and health in low-income social housing and quantifies residents' satisfaction, comfort, and building-related health symptoms.

2. Materials and methods

Social housing is affordable rental housing for low-income people with housing needs. In this study, residents were recruited from NSW public, community, and affordable housing. In total, indoor air and environmental quality were monitored in 106 households, and 109 residents participated in the questionnaire survey. A set of residential settings with different characteristics representing the social housing stock in Sydney were involved including a combination of housing types (e.g., one-story, multi-storey, single family, multifamily), housing characteristics (e.g., size, construction characteristics, age), and different locations (e.g., coastal areas, inland). They were located mainly in the Sydney metropolitan area from eastern to western suburbs, north-western and south-western areas, including also two houses in northern and southern coastal zones. Due to the microclimate characteristics of Sydney and reported higher ambient temperatures in the western suburbs [7], this study is further extended to western regional cities with five public dwellings. In this study, 51.4% and 41.3% of participating residents were living in public and community housing, respectively. The remaining 7% corresponds to low-income families who are not living in public and social housing.

A monitoring campaign was performed to obtain environmental data for the existing social housing building stock and assess the existing situation in terms of indoor environmental quality,

investigate potential health and energy impacts, assist in the understanding of the investments needed to achieve acceptable indoor environmental conditions (i.e., to avoid negative impacts on health), and facilitate the calculation of potential energy savings in social housing. The indoor air temperature, air relative humidity, and carbon dioxide (CO_2) data were continuously recorded from May 2018 to February 2019 using Indoor Air Quality Eggs version 2 Model D [8] placed in appropriate locations in the selected homes representing the common area where occupants spend most of their time during the day, i.e., living rooms. The sensors were positioned in a well-ventilated position in each dwelling, away from heat emitting sources, direct sunlight, or excessive moisture exposure while at the same time met the consent of the occupants. Measurements were recorded with an interval of one minute and then averaged over 30 minutes for analysis. In addition, 106 Logtag® TRIX-16 [9] with a recording interval of 30 min were placed in each dwelling to record the indoor air temperature. A questionnaire was completed by the residents participating in the study to collect information about energy bills, quality of the building envelope (e.g., type of windows), and IEQ (e.g., presence of mould), other features of the building type and energy profile (e.g., number of people sharing the household, time spent at home), and residents' health conditions and behaviours. The results are discussed in the following subsections.

2.1. General characteristics of the household in the study

The total households in NSW and Greater Sydney are more than 3,000,000 and 1,800,000 respectively, according to 2016 census data [10]. The average private household size in NSW and Greater Sydney for 2016 were equal to 2.6 and 2.8 persons [10], respectively, while the average per social housing family involved in the present research is of 1.8 people. Then, 54% of participating households contain only one person, while 32%, 6%, and 7% of household size are two, three, and over four persons per household, respectively. In the same year, the average age of the NSW and greater Sydney population was close to 38 and 36 years [10], while Table 1 shows that the average and the median age of the persons participating in the survey are 45 and 47 years, respectively.

Table 1. General characteristics of the households participating in the study.

No. of households participated in both monitoring and survey	109*
No. of residents in all dwelling	200
Average persons per household	1.8
Average occupiers' age [years]	45
Median occupiers' age [years]	47
Average area of the residence [m^2]	70
Average family income per fortnight (2018) [$]	~ 1,076
Average income per fortnight per person (2018) [$]	~ 600
Average education score (1–4) **	2.2
Average electricity bill per quarter [$]	271
Average electricity bill per quarter per floor area [$]	3.9
Average electricity bill per quarter per person [$]	150.5

* Total number of participants in the survey: 109. Total number of monitored household: 106.
** 1= No or low education, 2 = Secondary school, 3 = University, 4 = Diploma

The total population size in this study is made up of 76 (38%) males and 124 (62%) females, with 45% of the population aged between 18 and 60 years, 35 % over 60 and 22% below 18 years. Regarding the employment status of all people participating in the study, the employed people represent only 18% of the total, while the remaining 82% is divided into unemployed or non-active people (16%), students (28%), and retired people and disability pensioners (39%). The private households of NSW and Greater Sydney in 2016 were characterized by 89% of employed people and 6% of unemployed people. The

average (and median) of the declared household income value in 2018 is 1076 (800) AUD per fortnight per household and 600 (444) AUD per person in this study (Table 1). The median weekly personal income for people aged 15 years and over in Greater Sydney and NSW was 719 and 664 AUD for personal and 1750 and 1456 AUD for household, respectively [10]. The average electricity bill per quarter per household and per person is 271 and 151 AUD, respectively.

2.2. General characteristics of the dwellings in the study

About 71% of the surveyed buildings were constructed between 1950 and 2000 and 25% were built after 2000. In this study, there were only 5% very old stock dwelling (before 1950). All buildings were rented and none of the participants owned the dwelling. 60% of participating dwellings were apartment units (69) and 37 % were detached or semi-detached houses (40). The conducted inspections and surveys revealed the low thermal quality of the building envelope in the dwellings. All participating residences had single glazing windows (Table 2). 27% of dwellings were insulted, 28% had no insulation, and 54% of residents were not sure about the presence of the insulation in their building. During summer, 90% of households used portable fans or portable evaporative systems, 7% cooled by a split system, and 3% had no cooling system. Presence of mould, which may cause health issues if inhaled by vulnerable people [10], and condensation is also reported in 42% of dwellings. Mould and condensation primarily occurred in bedrooms (40%), 38% happened in wet areas (bathroom, laundry, kitchen), 17% in the living rooms, and 5% in all rooms.

Table 2. General characteristics of the dwellings participating in the study.

Average floor area of the dwellings [m^2]	69.5
Range of the floor area of the dwellings [m^2]	24-135
Average year of construction [-]	1975-2000
Percentage of insulated dwellings [%]	27%
Percentage of dwellings with double glazing windows [%]	0

3. Results and discussion

The survey participants spend on average 18 hours per day at home, which highlights the importance of indoor environmental condition and the quality of homes on comfort, health and satisfaction of residents. This is of importance considering the age group of residence over 60 years who spent 20 hours a day at home on average. 50% and 87% of resident have an income of 600-1,000 AUD and below 15,000 AUD per household per fortnight, respectively. Families with higher fortnightly income rate have up to 5 residents per household on average and pay higher rates for electricity bills, which reach to 500 AUD per quarter on average. Very low-income families (with about two people) pay lower rates for the electricity bills (i.e. 200 AUD) per quarter on average. 28% of total residents reported psychological disorder and among them, 48% suffer from depression. 38% of the residents who reported psychological disorder falls within the income group of 600-1,000 AUD. More than half of the residents have a health problem and the percentage of reported health problem is higher in female residents (40%) than males (14%). Airway (20%) and blood diseases (20%) are the most common health problems reported by the residents. When airway disease, allergy, and asthmatic symptoms are combined, it accounts for 32% of all reported disease, which highlights the importance of improving IAQ and IEQ in social and public housing. As it concerns the self-reported allergy condition, 32% of all residents suffer from allergy. 11 out of 42 children (26%) reported allergic reactions. Poor quality housing can harbour indoor allergens and asthma triggers (e.g., smoke, mould). The 38% of allergies is caused by environmental allergens, 28% is due to dust, 16%, 17%, and 1% to a certain food, medicine, and smoke (cigarettes, etc.), respectively. As shown in Figure 1, residences who reported pain or health problem had statistically significantly higher maximum air temperature indoors (33.6 ± 2.9 °C) compared to dwellings where

residents reported no health problems (32.7 ± 3.1 °C). No statistically significant difference was found considering allergies.

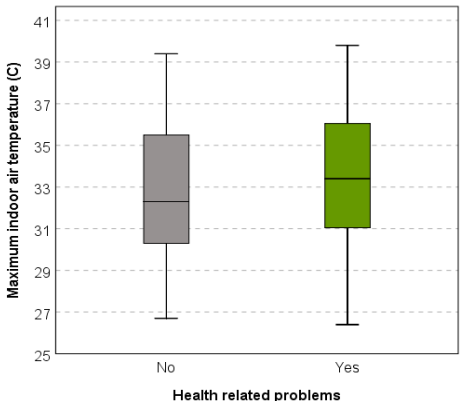

Figure 1. Box plots of health condition against maximum indoor temperature per dwelling.

The survey reported that 32% of participating residents were obese or very overweight, while only 4% were underweight. When body weight was clustered based on gender, the pattern was consistent. 24% of female and 9% of male residents reported to be overweight or very overweight. Only 37% and 27% of females and males had normal body weight, respectively. It was found that16% and 62% of residents were dissatisfied with their home thermal condition during winter and summer, respectively. Over 60% of residents felt very hot, and 23% felt slightly warm, making up 85% feeling on the warm side of the thermal sensation scale. Only 13% and 26% felt neutral during summer and winter, respectively. Residents were asked to report any hospital admission during summer 2018/2019. 3 out of 12 hospital admissions were associated with excess heat inside the residences. Further, occupants' perception of thermal comfort was investigated during summer 2018/2019 on a right-here-right-now basis. This indicates 51% of residents felt uncomfortably hot inside their home. When we analysed responses of 51 senior residents aged over 60 years, 57% felt warm and very hot, and 43% reported to feel neutral and slightly warm. This indicates senior group are slightly more dissatisfied of their thermal condition and more sensitive to higher indoor air temperature. In this study, CO_2 concentration fell well above the recommended thresholds in several investigated buildings. ASHRAE 62.1 [11] recommends a threshold of 1000 ppm for occupants' comfort, and NCC IAQ Verification Method suggests 850 ppm. Given the importance of air quality to human health and the considerable time social housing residents spend in their homes, it is important to improve IAQ in social housing dwellings. The elevated CO_2 observed indoors has a diurnal pattern similar to that of domestic activity, and it is positively correlated with occupant density (occupants per unit volume of the dwelling) [12]. Relative humidity was mostly above 60% during the monitoring period. Above 60% relative humidity, problems arise (e.g., moulds and fungus on surfaces) and this is supported by the responses provided by the residents. The indoor air temperature profile of the selected naturally ventilated households highlights the need for cooling when indoor air temperature exceeds the threshold for thermal comfort (setpoint temperature for cooling: 26 °C). Only for a short period, during mid-season, the indoor temperature in these houses fell within the comfort range. The maximum indoor air temperature recorded during the summer period, December-February 2018/2019, was 39.8 °C while the average indoor maximum temperature was 32.6 ± 3.02°C. This highlights the need for improved quality of buildings in social housing dwellings to avoid heat-related mortality and morbidity during heatwaves and extreme climatic condition in future. Given that cooling degree days in Western Sydney is almost three times higher than that in the central and northern parts of the city [8], improving building performance is of importance to reduce energy needs in social housing particularly those located in the western suburbs.

4. Conclusions

This study aimed to present the current IEQ of 106 low-income households in NSW and investigate problems associated with health, comfort, and energy. We combined physical measurements of thermal

environment and air quality with a subjective survey to evaluate occupants' satisfaction with their environmental quality, health, and energy use. Occupants' feedback on IEQ informs challenges of the low-income population to satisfy the required levels of the energy services in their dwellings that have negative consequences on different aspects of their life. The monitoring campaign shows indoor air temperature during summer fell much above the comfort limits, reaching 39.8 °C. Despite the demonstrated thermal adaptability of social housing residents, this led to a higher rate of dissatisfaction during summer. As it concerns IAQ, many of the investigated dwellings exceeded the recommended threshold with CO_2 falling well above 1000 ppm. This highlights the importance of building design and adaptation techniques to improve the quality of building envelope and passive design strategies to reduce the need for an active cooling system in social housing. 42% of dwelling reported mould and condensation their home. Based on the results of the survey, 28% of the overall population who participated in this study reported to have psychological disorders, 32% of all residents suffered from an allergy, and 54% of them reported specific health problems or pain. A priority should be given to improve IEQ in low-income households as residents are exposed to serious environmental and health risks. Efforts should be intensified to promote programs to improve the thermal performance of the low-income dwellings and programs to supply energy at low prices to satisfy basic needs. The outdoor microclimatic condition also needs to be improved, especially in Western Sydney, where air temperature can frequently be 7-10 °C hotter than in coastal suburbs [7]. A combination of advanced low-cost mitigation and adaptation technologies offers great potential for energy saving and contributes to improve the quality of life of the low-income population, provide comfort, and protect residents' health.

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