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Cost-Saving through Pre-Cooling: A Case Study of Sydney †

Shayan Naderi [1], Simon Heslop [2], Dong Chen [3], Iain MacGill [4] and Gloria Pignatta [1,*]

1 School of Built Environment, University of New South Wales (UNSW), Sydney, NSW 2052, Australia; s.naderi@unsw.edu.au
2 School of Photovoltaics and Renewable Energy Engineering, University of New South Wales (UNSW), Sydney, NSW 2052, Australia; s.heslop@unsw.edu.au
3 The Commonwealth Scientific and Industrial Research Organisation (CSIRO), Melbourne, VIC 3190, Australia; dong.chen@csiro.au
4 School of Electrical Engineering and Telecommunications, University of New South Wales (UNSW), Sydney, NSW 2052, Australia; i.macgill@unsw.edu.au
* Correspondence: g.pignatta@unsw.edu.au
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Abstract: Air conditioning is responsible for a considerable proportion of households' electricity bills. During summer afternoons when households usually run their air conditioners, the retail time-of-use electricity tariffs are highest, and there is a peak demand in the electricity network. Pre-cooling is a method to shift air conditioning demand from peak hours to hours with lower demand and cheaper electricity tariffs. In this research, the pre-cooling potential of nine different types of residential housing in Sydney constructed with different star ratings and construction weights is evaluated. Star rating is the method to represent the annual heating and cooling requirements of buildings in Australia. Results highlight that pre-cooling produces cost saving for most of the days in 6-star and 8-star buildings. For 2-star buildings, pre-cooling sometimes leads to higher electricity costs. Moreover, pre-cooling improves thermal comfort, especially in 2-star light and medium weight buildings.

Keywords: air conditioning; load shifting; energy efficiency; thermal mass; energy storage; residential buildings; Australia

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1. Introduction

The ownership of air conditioning (AC) systems in Australia has been growing in the past two decades, increasing from 35% in 2000 to 75% in 2014 [1]. AC units are run extensively during extreme temperatures and contribute to a considerable proportion of peak demand in the Australian National Electricity Market (NEM) [2,3]. Electricity generation units are committed based on merit order economic dishpatch, which brings units with higher marginal cost into operation during peak hours. These peaks also are a significant driver of network expenditures. These electricity and network costs are reflected in the higher peak electricity tariff rates paid by households at these times, resulting in higher electricity bills [4].

One method for shifting peak AC demand to times with lower demand and cheaper electricity tariff rates is using building thermal mass as a virtual battery. Thermal energy can be injected into, or removed from, thermal mass by increasing or decreasing its temperature [5]. Through pre-cooling, the temperature of thermal mass is reduced during off-peak hours. When the peak starts, AC is switched off, and the indoor air temperature starts to rise slowly. The cooled thermal mass absorbs the heat gains and reduces the pace at which the indoor temperature rises. Consequently, AC remains off for a period during peak hours. Pre-cooling reduces household electricity costs due to the avoided demand during times with expensive electricity tariff rates. Moreover, by running AC when the indoor temperature is low, AC can work with higher mechanical efficiency.

It has been reported that the thermal mass characteristics, quantity, and thickness affect cost-savings and peak AC demand reduction for a pre-cooling scenario [6]. Moreover, climate, pre-cooling duration, setpoint temperature during pre-cooling, and setpoint temperature during peak hours, change the benefits of pre-cooling scenarios [5,7]. Several studies have been conducted to investigate how the above parameters affect pre-cooling cost saving and peak AC demand reduction [8–11], by proposing different pre-cooling scenarios in terms of duration, setpoint temperauture, and considering different electricity tariff rates. Furthermore, some researchers have developed optimization frameworks to find the best pre-cooling strategy for a given case study [12–14]. Optimization frameworks trade-off between the possible peak AC demand reduction and the amount of extra energy used to pre-cool the building. Based on the thermal dynamics of the building and the ratio of peak to off-peak tariff rate, the optimizer can find the optimum temperature setpoint trajectory [13].

So far, most of the studies have been conducted for case studies in the USA [15–17], and studies for Australian building stock are limited to a few works on commercial buildings [18,19]. Since afternoon residential AC demand is considerable in Australian cities [20], pre-cooling of residential buildings might offer cost-saving to households and the electricity network, and reduce peak AC demand. This gap motivated the authors to simulate pre-cooling of different types of buildings in Sydney.

2. Materials and Methods

The case studies under investigation and the modeling approach are introduced in the following sub-sections.

2.1. Case Study Building

Pre-cooling of nine different housing types located in Sydney is simulated to understand the potential cost saving for households. The buildings are categorised by their star rating and their construction weight to represent old, new, and high efficiency dwellings. The star ratings of the investigated buildings are 2-star, 6-star, and 8-star, for three different construction weights, light, medium, and heavy. The construction materials used are based on common construction materials used in New South Wales according to Australian Housing Data published by CSIRO [21]. The prototype building has four bedrooms with a total of 160 m^2 floor area. Considering the floor area of the building, a large non-ducted split system with a 25 kW cooling capacity and energy efficiency ratio of 3.5, based on the historical AC registration database [2] is selected. The simulated period is one summer, from 1 December 2018 to 28 February 2019. The weather data is collected from the nearby weather station, located in Mascot, Sydney.

2.2. Modeling

Pre-cooling is presented in this study as an optimization problem. It is formulated as a Linear Programming (LP) problem in Pyomo [22] to minimize daily AC electricity cost and thermal discomfort simultaneously by finding the optimum temperature setpoint trajectory. The thermal comfort range is 80% acceptability, defined by the adaptive thermal comfort model [23,24].

In the pre-cooling scenario, the indoor temperature can be set lower than an upper threshold. The optimizer can pre-cool the building if it leads to cost-saving, or it avoids thermal discomfort. In the baseline scenario, the AC is only switched on when the indoor temperature exceeds the upper threshold. The upper threshold is defined as neutral temperature [24] during off-peak hours and is the maximum allowable temperature in the thermal comfort range during peak hours.

Since the investigated building has more than one thermal zone, an Aggregated Dynamic Thermal Model (ADTM) is used to model its thermal dynamics. ADTM projects states (indoor temperature) of a multi-zone building into one state [25]. The volume fraction of zone j, ε_b^j, is used as the weight to represent the contribution of zone j in the aggregated state. Then, an AutoRegressive with eXogenous (ARX) variables model is fitted to present the change of the aggregated state according to AC demand, outdoor temperature, and solar radiation.

3. Results

The findings are daily cost savings for each case study building and the sum of thermal discomfort reduction during the summer after implementing pre-cooling. Figure 1a illustrates the potential cost saving in days with non-zero AC demand. Pre-cooling in 6-star and 8-star buildings leads to positive cost-saving for almost all days over the study period. The figure also shows that pre-cooling in 6-star medium and heavy weight buildings and all 8-star buildings results in more than 50% cost saving for all days. Meaning that people can save at least 50% of the electricity cost attributed to powering their AC. In 2-star buildings, especially those with light weight construction materials, the negative cost savings can be observed on some days. On days with higher maximum outdoor temperature, the negativity increases, and some households should pay higher electricity costs than the baseline scenario, if they pre-cool their building. The reason is that on hot days, the building is pre-cooled to reduce or avoid thermal discomfort, even if it leads to higher daily electricity costs. Although the building is pre-cooled, the AC cannot be switched off during peak hours. It might be due to the inability of 2-star buildings to retain the coolness for a period of time, and also their fast response to the ambient. A significant proportion of positive savings in 2-star buildings is less than 50%. There are also a few points for 2-star heavy buildings in the figure, which indicates a few days with AC demand in these buildings.

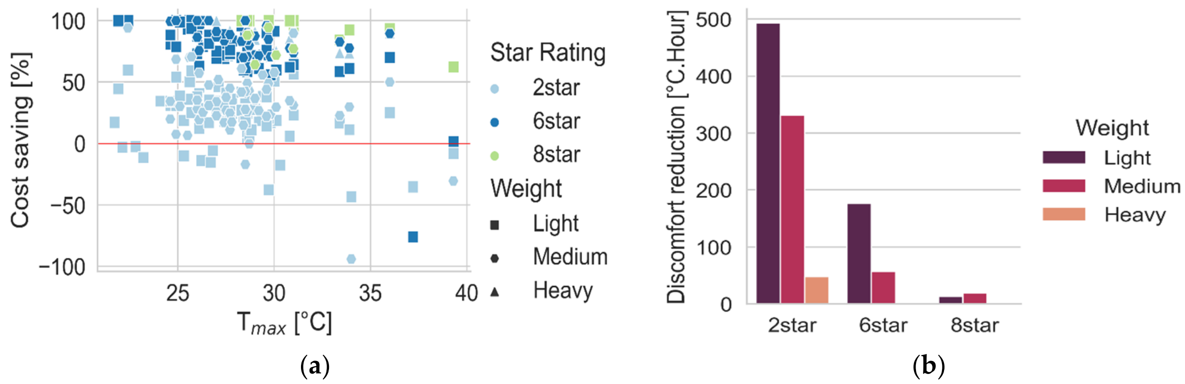

Figure 1. (**a**) Potential cost-saving vs. maximum outdoor temperature, and (**b**) thermal discomfort reduction in different building types.

Figure 1b presents thermal discomfort reduction through pre-cooling. Although pre-cooling in 2-star buildings is not economically profitable on some days, it significantly reduces thermal discomfort. Thermal discomfort in 2-star light weight buildings can be reduced by around 500 °C × hour over the summer period, compared with the baseline scenario. In other words, occupants will feel 500 °C × hour more thermal comfort over this summer. Thermal discomfort reduction is also considerable in 6-star light and medium weight buildings. Since the star rating of the majority of the existing dwellings is less than or around 2-star, our results highlight a significant thermal discomfort reduction for people who live in Sydney.

4. Conclusions

The present study aims to assess the potential benefits of pre-cooling for households living in Sydney. The pre-cooling of nine different types of buildings, with different star ratings and construction weights, are simulated with the objective to minimize air conditioning electricity cost and thermal discomfort simultaneously through pre-cooling. The results highlight that on some days with high outdoor temperatures, pre-cooling might not lead to cost-saving. However, it highly improves the thermal comfort of occupants, especially in 2-star light and medium weight buildings. Furthermore, pre-cooling is always economically beneficial in 6-star medium and heavy buildings and all 8-star buildings, resulting in more than 50% cost saving for those households.

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