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Peak load reductions: Electric load shifting with mechanical pre-cooling of residential buildings with low thermal mass

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ABSTRACT

This study uses an advanced airflow, energy and humidity modelling tool to evaluate the potential for residential mechanical pre-cooling of building thermal mass to shift electricity loads away from the peak electricity demand period. The focus of this study is residential buildings with low thermal mass, such as timber-frame houses typical to the US. Simulations were performed for homes in 12 US DOE climate zones. The results show that the effectiveness of mechanical pre-cooling is highly dependent on climate zone and the selected pre-cooling strategy. The expected energy trade-off between cooling peak energy savings and increased off-peak energy use is also shown. The best pre-cooling results (more than 75% energy use shifted away from peak while minimising the total energy penalty) for most climates were obtained using a medium (5 h) pre-cooling time window with a shallow (23.3 °C) pre-cooling set point temperature. All of the pre-cooling strategies investigated caused the annual cooling energy demand of the simulated buildings to increase. Additionally, all of the pre-cooling strategies shifted at least 50% of the on-peak cooling loads away from a peak period window of 4pm–8pm in all climate zones.

1. Introduction

According to the US Energy Information Administration, 97 million US households contained mechanical air conditioning systems in 2009, compared with 74 million households in 1997 [1,2]. This increasing use of residential air conditioning is placing a large strain on electricity distribution grids. During particularly extreme weather, the extra cooling load can cause electricity demand to outstrip supply, leading to widespread blackouts. Consequently, there is currently a drive toward reducing the maximum instantaneous load on power grids. ‘Peak energy demand’ refers to the time of day when loads on the electricity distribution infrastructure reach a maximum. During the summer months this tends to happen between 16:00 and 20:00 when high outdoor temperatures coincide with people returning home from work, resulting in high residential air-conditioner use.

During peak periods the extra demand on the grid is met by increasing capacity via the operation of power plants with a higher marginal cost and greater CO_2 emissions than power plants used to meet base load (Mahone et al. [3] discuss this in detail for California). This increases the generation cost for each kilowatt-hour for the utility company. The cost is then passed down to the consumer via increased utility rates. Utility companies in the US are beginning to offer tariff-based incentives to consumers to help reduce peak energy demand and hence cost (e.g. Herter & Wayland [4]). An example of an incentive is ‘TOU’ (Time of Use) schemes, where a schedule is set by the utility company offering cheaper energy prices during off-peak times and more expensive energy during on-peak times. This encourages consumers to shift their main energy use to periods when energy generation is less expensive and the overall demand may be met more easily. Other mechanisms for reducing peak energy demand include solar shading, adoption of photovoltaics, and load shedding (reducing total electricity use). Reductions in peak cooling demand have been demonstrated in theory and through field tests by either increasing the amount of thermal insulation used within a wall [5], or by increasing the thermal mass of the wall [6–8]. Al-Sanea and Zedan [9] showed that peak cooling loads in Riyadh could be reduced by up to 26% by optimising summertime thermostat temperatures.

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Pre-cooling is a strategy that attempts to remove some of the increased peak demand on the electricity grid by shifting the cooling load to off-peak times. The cooling thermostat set points are reduced in the period preceding the peak period in order to force the air-conditioner to operate. This allows the air conditioner to cool the thermal mass of the house while electricity prices and generation costs are lower. The set points are then raised at the start of the peak period, allowing the building to coast through. As the building takes time to warm up, the operation of the cooling equipment is delayed during the hotter peak period. Additionally, the efficiency of air-conditioners (Energy Efficiency Ratio or EER) increases with lower outdoor temperatures, so their energy consumption is less while operating during off-peak periods. The lower outdoor temperatures increase the basic Carnot efficiency and have been found to be significant in commercially-available vapour-compression-based heating and cooling systems [10]. Using the thermal mass of a building to impact cooling (and heating) loads can be exploited to reduce costs, but this requires intelligent control of the building HVAC systems [11]. Braun et al. [12] used simulations to demonstrate a 40% decrease in total cooling costs from using a thermal mass control strategy.

Previous studies have shown that pre-cooling houses using mechanical air conditioners can increase the total annual cooling energy [13,14]. However, by shifting loads away from the times of peak electricity demand, the need for running higher carbon-producing power plants during peak periods (in some US States but not all) can be reduced. As well as potential economic benefits of pre-cooling and TOU tariffs, shifting cooling loads to different parts of the day can also help utilise renewably-generated electricity more effectively, such as electricity generated by wind farms. This means that the net carbon output can be reduced, even though more energy is used. The shift of electrical loads away from the peak periods can also contribute to grid reliability and reduces the risk of power outages or brownouts.

Many studies have shown that pre-cooling thermal mass can reduce the cooling load of commercial buildings or shift the cooling load away from times of peak demand [15–22]. However, there is very limited literature on pre-cooling residential buildings, and the work that has been done is typically restricted in scope to the climate of California. Beutler [23] demonstrated via simulation that pre-cooling using mechanical air-conditioning could reduce annual peak period residential air-conditioner operation by between 75% and 84% in California. Simulation results from a study by the Davis Energy Group for a US utility company in California suggest that, when combined with night ventilation, pre-cooling could save up to 97% of residential peak electricity consumption [13]. Although total annual electricity consumption increased by 26%, field testing from the same study yielded annual electrical peak savings of 88%. This is in agreement with Katipamula and Lu [14] who also showed using a simplified building electricity load model, that pre-cooling residences can reduce peak cooling loads, but at the expense of more total energy used. A more recent study by the Davis Energy Group reports that pre-cooling can shift up to 100% of residential peak cooling loads away from the peak period in high performance homes in hot-dry climates [24]. A Sacramento-based pilot project in California [25] showed that pre-cooling strategies can provide residences with 60% cooling energy savings during peak times, when combined with TOU-CPP (critical peak pricing) tariffs and real-time energy information for home owners. Further field studies in Sacramento demonstrated up to 43% peak load savings from mechanical precooling [26].

This study looks at the potential for mechanical pre-cooling to shift peak electricity load away from the peak demand period in low-mass residential buildings. A computer modelling approach was used to study the annual cooling loads of six pre-cooling strategies in 12 different US climate zones. Due to the diversity in US climates, the results presented in this paper are applicable to a large range of countries and so fill a gap in the existing literature. The results of the simulations were used to assess the balance between on-peak energy reductions and off-peak energy consumption, while still providing good thermal comfort. As the pre-cooling strategies employed rely solely on changing thermostat temperature set points, no additional equipment or controllers are required to invoke the strategies. This means that the pre-cooling strategies can be applied to any mechanical air conditioning equipment that is controlled using a programmable thermostat.

2. Method

In this study, the REGCAP (register capacity) building simulation tool was used to investigate the peak cooling energy demand reduction potential of mechanical pre-cooling. For each simulation there was a reference case used to determine the impact of mechanical pre-cooling on building cooling loads and electricity use. The building loads included conduction and radiation effects for both opaque and transparent envelope components. Airflow between the home and its environment is also a significant load. The simulations included natural infiltration due to wind and indoor/outdoor temperature differences, as well as ASHRAE Standard 62.2 [27] compliant continuous whole-house mechanical exhaust ventilation. For this study the peak cooling time was defined as 16:00 to 20:00. This time period was selected as it is the 4 h period after the thermostat temperature change when the air conditioning system is operating at maximum capacity to reduce the indoor temperature. The results of field monitoring studies such as Herter et al. [28] show that is a reasonable time window for defining the cooling peak period.

2.1. Building simulation tool

The energy consumption of the modelled houses was evaluated using the REGCAP residential building simulation tool. The REGCAP model, developed and validated at the University of Alberta [29] and Lawrence Berkeley National Laboratory [30], is an advanced residential HVAC model that combines ventilation, heat transfer, and moisture models to determine annual residential energy use as a function of building characteristics and location, and has been used in previous studies e.g., Turner et al. [31] and Logue et al. [32]. REGCAP was specifically written to investigate residential HVAC system performance and control strategies. The attic volume and house volume are treated as two separate, well-mixed zones (mixing occurs instantaneously), but connected for airflow and heat transport. Energy, mass and moisture are conserved and flows are calculated iteratively. Once convergence criteria have been satisfied the simulation moves onto the next time step. REGCAP includes heating and cooling system airflows to and from the house and, via duct leakage, the attic. REGCAP also allows the modelling of distributed envelope leakage and mechanical system airflows for ventilation, heating and cooling, as well as individual localised leaks.

Key REGCAP inputs are building air leakage characteristics (total leakage and leakage distribution), time resolved weather data, weather shielding factors, building and HVAC equipment properties, and auxiliary fan schedules. REGCAP uses an HVAC equipment model that uses heating and cooling system capacities and efficiencies to determine energy consumption. A ducted, forced-air HVAC system with a gas-fired furnace is simulated for heating and a vapour-compression air conditioner is simulated for cooling. The gas furnace heating capacity is fixed for all conditions. Heat produced by the furnace is added to the house air via the supply register. In the case of the air conditioner, the cooling system performance is