Mitigation of Peak Cooling Demand through the Combination of Residential Zoned Cooling and Window Shading:

A Building Simulation Case Study

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Abstract

The present study expands on previous building simulation work concerning the potential benefits of residential zoned cooling systems during peak summer days. Such zoned systems provide an opportunity for peak reduction on hot and humid days when the electricity peak is largely caused by increased space cooling demand. In the previous study, control strategies for different occupancy profiles were considered and their impact on peak and cooling energy reduction were compared. The present study builds on these results by considering the benefits of shading as a passive means of reducing the peak cooling load.

The analysis is based on integrated building energy simulations of a newer-vintage house using the zoned cooling system model in conjunction with the expanded set of shading models. Total cooling energy demand, peak cooling power reductions and their impact on evening recovery times are examined.

It was found that zoned control strategies alone can yield significant peak power reductions, but the long recovery periods limit their practical application. Only with between-pane or outdoor shade configurations can very large reductions can be realized without compromising occupant comfort during the evening recovery period.

1 Introduction

Demand for electricity in Ontario is highest during hot and humid summer days and is largely caused by increased use of air conditioners. According to the Ontario Energy Board, as the low-cost generating capacity from nuclear and hydroelectric stations cannot meet the demand during the peak, the province uses more expensive hydrocarbon generating sources like coal-fired and natural gas-powered plants. Electricity customers are then charged at a premium during the peak period between 11:00-17:00 based on the time-of-use pricing structure (Ontario Energy Board 2013). Reducing the overall electricity demand during summer-time peaks is both desirable from the perspective of cost reduction to the homeowner, and province, as well as increased air quality from the reduced operation of hydrocarbon fuelled generating sources.

One strategy for mitigating peak cooling demand in the residential sector is to implement zoned cooling systems in multi-storey dwellings. Such systems deliver more balanced cooling to each thermostatically controlled zone and thus ameliorate the temperature stratification problem common in single thermostat systems. Energy and peak power savings can be realized by applying thermostat setback control to unoccupied zones during peak times.

Another more traditional but often overlooked approach is window shading, as the solar heat gain through windows accounts for a large fraction of the sensible cooling load in many homes during peak times. To be most effective, shading devices should be placed on the outdoor side where any solar energy absorbed by the shade can be dissipated to the environment.

This paper presents a building energy simulation case study in mitigating the peak cooling load in a newer-vintage two-storey home using a combination of zoned cooling, the active approach, and window shading, the passive approach. A comparison of zoned cooling to standard single thermostat air conditioning systems has been carried out in a previous study by Lomanowski and Haddad (2010). In that study it was shown that the effectiveness of a zoned cooling system can be significant, depending on the thermostat setback scenario. However, more aggressive peak shaving strategies were shown to result in longer evening recovery times due to the heat build up during setback periods. The current study extends that analysis by considering various shading strategies in addition to zoned cooling setback scenarios.

The approach to modelling the combined effect of zoned cooling and window shading relies on an established air conditioning model and a suite of well validated solar and thermal shading algorithms, both implemented in the integrated building energy modelling tool,ESP-r.

2 Methodology

ESP-r Model

The present study employs the same ESP-r model as in the previous study (Lomanowski and Haddad, 2010); namely, the Canadian Centre for Housing Technology (CCHT) (Swinton, Moussa and Marchand, 2001) test house, shown in Figure 1. This house is built to the R2000 standard with several of its characteristics listed in Table 1. The model includes a simulated occupancy of two adults and two children, including sensible and latent gains to the first and second floors of the house from the use of lighting, refrigerator, stove, dishwasher, clothes washer and dryer and other small kitchen appliances. Table 1 provides more detail on the operational gains.

Table 1: CCHT house characteristics.

Liveable Area	210 m^2 (2260 ft^2), 2 storeys
Insulation	Attic: RSI 8.6, Walls: RSI 3.5, Rim joists: RSI 3.5
Basement	Poured concrete, full basement Floor: Concrete slab, no insulation Walls: RSI 3.5 in a framed wall.
Exposed floor over the garage	RSI 4.4 with heated/cooled plenum air space between insulation and sub-floor.
Windows	Low-e coated, argon filled windows, U-value: 2.2 W/m^2K, SHGC: 0.68 Area: 35.0 m^2 (377 ft^2) total, 16.2 m^2 (174 ft^2) South Facing
Air-tightness	1.5 air changes per hour @ 50 Pa (1.0 lb/ft^2)
Internal gains (sensible)	7:00-9:00: 1.5 kWh, 12:00-13:00: 0.5 kWh (C0,C2 only), 18:00-22:00: 5.2 kWh
Internal gains (latent)	7:00-9:00: 0.4 kWh, 12:00-13:00: 0.2 kWh (C0,C2 only), 18:00-22:00: 0.5 kWh

Zoned Cooling System

A notable feature of the ESP-r model used in the previous (Lomanowski and Haddad 2010) and present studies is the upgrade of the existing unitary split air conditioning model (Haddad

2004a) with zoning capabilities. The air conditioning model estimates the performance of an air-source heat pump in the context of an hour-by-hour integrated building simulation by linking the ESP-r zone time-step temperature controller with a correlation-based calculation method. The predicted cooling load for the time step is used to set the part-load ratio (PLR) of the equipment. This PLR is then used to predict the coefficient of performance (COP) of the heat pump. The steady-state total cooling capacity and COP are calculated at each time step using appropriate correlations and account for the effect of the inlet wet-bulb temperature to the evaporator coil, the ambient dry-bulb temperature, and the inflow rate over the indoor coil. The cooling coil Bypass Factor is corrected for the inflow rate. The dry cold air from the cooling coil is then coupled to the space energy and moisture at each time-step. The model was validated using steady state (Neymark and Judkoff 2002, Haddad 2004a) and transient (Neymark and Judkoff 2004, Haddad 2004b) cooling test cases. In these test cases predictions from air conditioning models from various well recognized building energy analysis tools are documented to form a set of reference results. Results for the transient test cases from ESP-r were compared against the reference results with very good agreement.

The zoning modifications accommodate zoned thermostat control scenarios whereby the air conditioning capacity is directed to each thermostatically controlled zone independently. Residential forced-air packages typically achieve this by means of damper controlled ducting systems. If more than one zone is calling for cooling simultaneously the system capacity is divided into the individual ducting circuits for which the overall air-flow rate is adjusted as a function of the number of calling zones by means of a variable speed fan.

In the CCHT ESP-r model the first and second floors are defined as independent thermostatically controlled zones. As a result of pressure gradients established by the zoned air supply, the air-flow dynamics of a zoned system can have a significant impact on the inter-zone temperature distribution. Inter-zone air flow and infiltration were thus resolved by means of a pressure driven mass flow network. ESP-r's flow network solver is coupled to the zone thermal balance, thus capturing the interaction between air-flow changes and their influence on the conditioned space. The theoretical basis of flow network modeling in ESP-r is well documented (e.g., Hensen 1991, Beausoleil-Morrison 2000, Hand 2011).

Inter-zone air flow due to the zoned air-handling unit is modeled by means of constant volume flow components of the mass flow network which are placed between the second floor, first floor and basement nodes. The house air flow balance depends on the individual zone thermostat call states which determine the supply fractions to each zone. The Details of this scheme are given in (Lomanowski and Haddad 2010). The synchronization of the mechanical air-flow balance with the delivery of cooling capacity to the air-point in each controlled zone therefore captures the dynamics of a zoned supply-return system delivering conditioned air into the space.

Infiltration is modeled in the explicit mass flow network by imposing a set of wind driven pressure coefficients on external boundary nodes and coupling the boundary nodes to internal zone nodes through a flow restriction component on each external wall in each zone. To tune the air leakage characteristics of the CCHT model, the Alberta Infiltration Model (AIM-2) was used as a reference to adjust the flow network orifice sizes until the desired air leakage characteristics were observed. Details of the AIM-2 model can be found in (Walker and Wilson 1990).

With the integration of ESP-r's on-off temperature controller using sub-hourly time resolution in combination with the zoned cooling system model and the explicit air-flow network model, the performance of a forced air zoned cooling package is well resolved.

Window Shading

ESP-r's Complex Fenestration Construction (CFC) facility was used to model windows with shading devices. CFCs are a derivative of ESP-r's standard multi-layer constructions in which each layer of the construction assembly is represented by thermo-physical nodes. These nodes are connected by resistive and capacitive terms that represent heat flow paths and storage capacities based on the ascribed thermo-physical properties of the construction layers (see Chapter 3 in Clarke 2001).

The CFC approach builds on this nodal-network scheme by providing additional resistive couplings needed to describe a generalized multi-layer array consisting of glazing, shading, and fill gas elements. Couplings to non-adjacent layers are needed to capture radiative and convective heat transfer across shading layers. The reader is referred to (Wright 2008 and references therein) for a description of the underlying solar and thermal models as well as to (Lomanowski 2008 and Lomanowski 2011) for details of the CFC numerical scheme implementation in ESP-r. A series of calorimetric measurements in a controlled environment test chamber by Kotey et al (2009) were in very good agreement with model predictions for various shading configurations.

The result of the CFC implementation in ESP-r is a window shading module that captures the complex transport of heat and solar energy in a generalized manner. The resulting bifurcation of the total solar heat gain into the transmitted and thermal fluxes to the indoor space are captured quite naturally. Thus, the type, geometry, colour and placement of the shading layer may be scrutinized and the influence of the shading configuration on the energy balance of the conditioned space assessed. The current state of the convective heat transfer models for indoor and between-panes shading configurations (e.g., Collins et al 2008, Wright 2008) impose limits on the available glazing-shading CFC combinations such that only one shading layer may be specified, its placement within the glazing assembly being entirely general. This limitation avoids the possibility of assigning two adjacent shading layers, which cannot currently be handled by the convection model.

Recent modifications to the CFC facility provide the user with more shading types in addition to the original implementation of Venetian slat-type blinds. The updated CFC capabilities now encompass the calculation of effective optical properties for pleated drapes, roller blinds and insect screens, thus extending the CFC solar and thermal routines to handle these additional shading types. It is worth mentioning for users of ESP-r that, in contrast to the original implementation for which a third party glazing-shading editor was required, configuring a CFC is now a completely self contained process. The user may now make use of the CFC layers database for constructing the glazing – shading - fill gas assembly. This database also includes the full set of International Glazing Database (IGDB) entries.

Simulation Parameters

To assess the performance of the combination of active zoned cooling and passive window shading strategies on the cooling electricity peak demand and total energy, a parametric analysis was carried out using the CCHT house ESP-r model configured with a sub-hourly simulation time-step resolution (12 time-steps per hour) with weather boundary conditions corresponding to a hot, humid and sunny summer peak day. Specifically, Toronto weather data for August 31, 2000 was used (Figure 2) and a 5 day start up duration was selected with the preceding start up day conditions similar to that of the peak day.

Three zoned control strategies were selected to represent typical thermostat schedules in a two-storey house with independent thermostat control on each level:

- Control scenario **C0**: The reference scenario. Both first (main) floor and second (upstairs) floor thermostats are set to 23°C for the entire 24 hour simulation period.

- Control scenario **C1**: Occupants are away during the morning and early afternoon. Cooling is turned off to both levels during the day. Cooling to the first floor resumes at 15:00 and to the second floor at 19:00. In this scenario the occupants occupy the first floor in late afternoon and early evening thus cooling to the first floor is turned on prior to their arrival in order to remove the accumulated heat. The second floor temperature is recovered later in the evening.
- Control scenario **C2**: Occupants are at home occupying the first floor level during the daytime. Cooling is turned off to the second floor until 19:00, at which time the recovery period starts.

Figure 3 shows the detailed control schedule for scenarios C1 and C2. The thermostat is set to 23°C during a cooling period; otherwise cooling to the zone is turned off.

In addition to the zoned cooling control scenarios, several shading configurations were selected that represent a typical range of window shading options available to the homeowner. These include roller and Venetian blinds in outdoor, between-panes (mid) and indoor configurations, indoor pleated drapes, and outdoor insect screens. In all the configurations, double glazing with low-e coating was used. An argon fill insulated glazing unit (IGU) was specified in all cases except for between-pane shade cases where an air-filled cavity was used instead. A light and dark option was selected for each type of shading device. For those shading devices consisting of a mesh material (roller blinds, pleated drapes, insect screens), a relatively closed and open mesh were also considered. For the Venetian blind case, two slat angles were selected to represent a fully closed and partially open blind. The shading cases are summarized in Table 2.

Table 2: Shading configuration case matrix with shading categories defined as: REF – reference, VBD – Venetian blinds, DRP – pleated drapes, RLD – roller blinds and BUG – insect screens. The shading fabric direct transmission is given in percent.

		Placement		
		Outdoor	**Mid**	**Indoor**
REF	no shading		X	
VBD	30° slat angle, light	X	X	X
	30° slat angle, dark	X	X	X
	80° slat angle, light	X	X	X
	80° slat angle, light	X	X	X
DRP	light, 35%			X
	dark, 35%			X
	light, 1%			X
	dark, 1%			X
RLD	light, 14%	X	X	X
	dark, 14%	X	X	X
	light, 5%	X	X	X
	dark, 5%	X	X	X
BUG	loose mesh, 73%	X		
	tight mesh, 37%	X		

The azimuthal orientation of a window with respect to the solar incidence angle dictates how effective a window shade will be for a given time of day, season and latitude. For this reason, three window shade deployment strategies were selected. In the reference scenario, none of the windows are shaded. In the standard scenario, all of the windows are shaded equally. In the south-only scenario, the south-facing windows are shaded, with the remaining east-facing, west-facing and north-facing windows unshaded.

The configuration of the air conditioning model was based on a commercially available residential system composed of a central air handling unit with circulation fan and cooling coil located in the basement and a compressor/condenser fan unit located outdoors. Table 3 lists the specifications for a 2 ton (7033 W) unit used in the model. The circulation fan flow rate depends on the number of zones calling for cooling. The fan settings are: a maximum of 800 ft^3/min serving all three zones simultaneously, or 640 ft^3/min for two zones and one zone. It is assumed that no dedicated cooling is required for the basement; therefore the flow rate for the zoned system is constant at 640 ft^3/min regardless of the calling state of the first and second floor zones. The circulation fan is configured to operate in tandem with the compressor.

Combining all of the above model input parameters, a total of 177 simulation cases were generated. The simulations were carried out and the results post-processed using a batch run scripting technique.

Table 3: Air conditioner specifications.

Rated Capacity[1]	7033 [W]
Rated COP[1]	3.43 (SEER 13)
Max. flow rate	800 [ft^3/min]
Max. circulation fan power	300 [W]
Condenser fan power	150 [W]
Sensible Heat Ratio[1]	0.76

[1]at ARI rating conditions (26.7°C T_{dry_bulb} , 19.4°C T_{wet_bulb})

3 Results

Figure 4 shows the main simulation outputs; namely, the time evolution of the total air conditioner electrical power (compressor + circulation fan), first floor and second floor temperatures. The temperature traces are shown at the true time-step resolution, while the air conditioner electrical power is averaged over the hour to smooth out the on-off cycles, which may occur many times an hour as indicated by the temperature oscillations. Figure 4a, 4b and 4c contrast the unshaded reference cases of each zoning control scenario (C0, C1, C2) with an outdoor Venetian blind window shading configuration.

The results of the parametric analysis are shown in the remaining figures. The effect of the set of window shading configurations on the total energy over the 24 hour simulation period and the average power between the hours 12:00-18:00 is shown in Figure 5. The chosen peak period largely coincides with the Ontario time-of-use electricity price summer weekday peak period from 11:00-17:00. Only the cases from control scenario C0 are shown, and the placement of the shade (indoor, mid, outdoor) is designated by colour. Similarly, Figure 6 presents the total energy vs. peak power results of all cases with all windows shaded as well as the reference non-shaded cases. Figure 8 shows an overlay on top of the results from Figure 6 of the cases with only the south windows shaded.

Finally, Figure 7 shows the impact of the set of window shading configurations and control scenarios C1 and C2 on the second floor recovery time (Figure 7a) and peak temperature (Figure 7b) vs. the peak period average power. The recovery time is calculated as the difference between the time when the second floor temperature falls below 24°C and the start time (19:00) of the evening cooling period for both control scenarios C1 and C2. The second floor temperature recovery is more clearly demonstrated in the second floor temperature decay starting at 19:00 in Figures 4b and 4c.

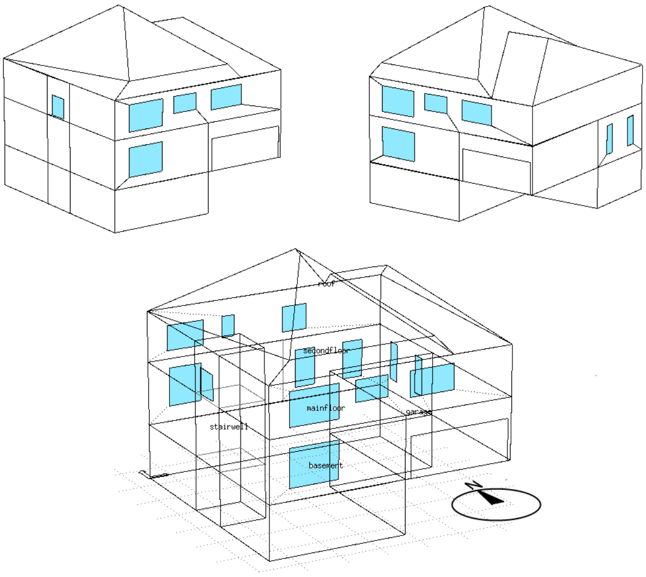


Figure 1: Geometry of CCHT house model in ESP-r (windows shaded blue).

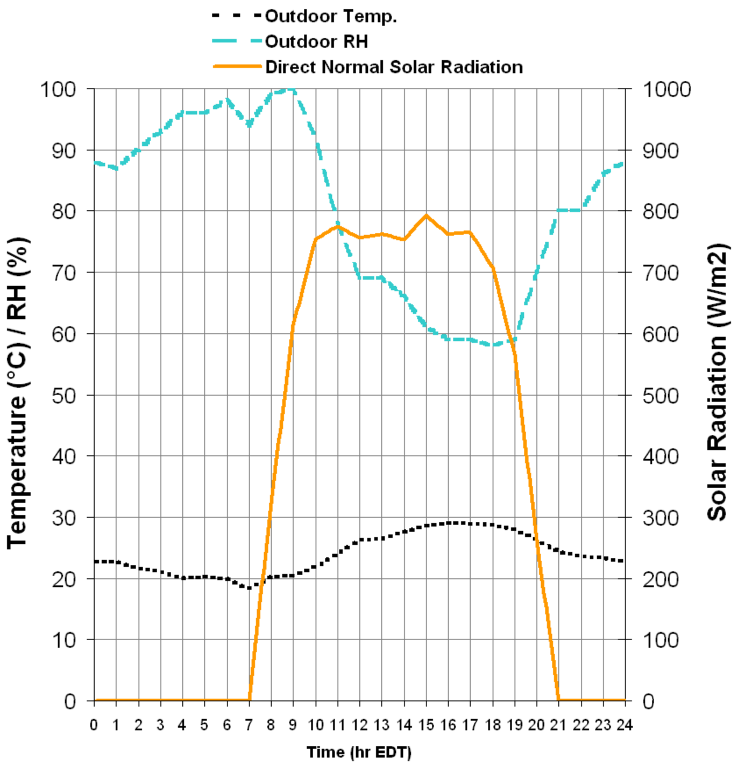


Figure 2: Weather data used in the ESP-r model. Data is from August 31st, 2000, Toronto.

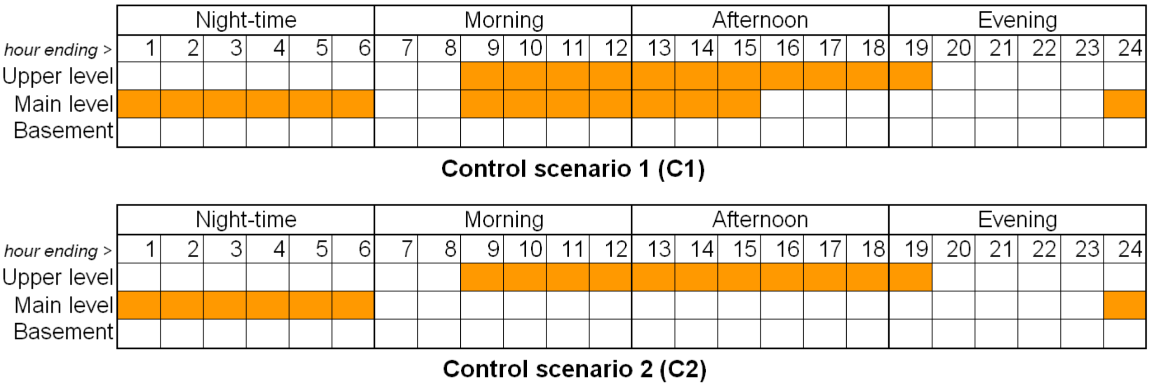


Figure 3: Zoned control scenarios. Cooling is turned off during the shaded periods, otherwise the thermostat setpoint is 23°C.

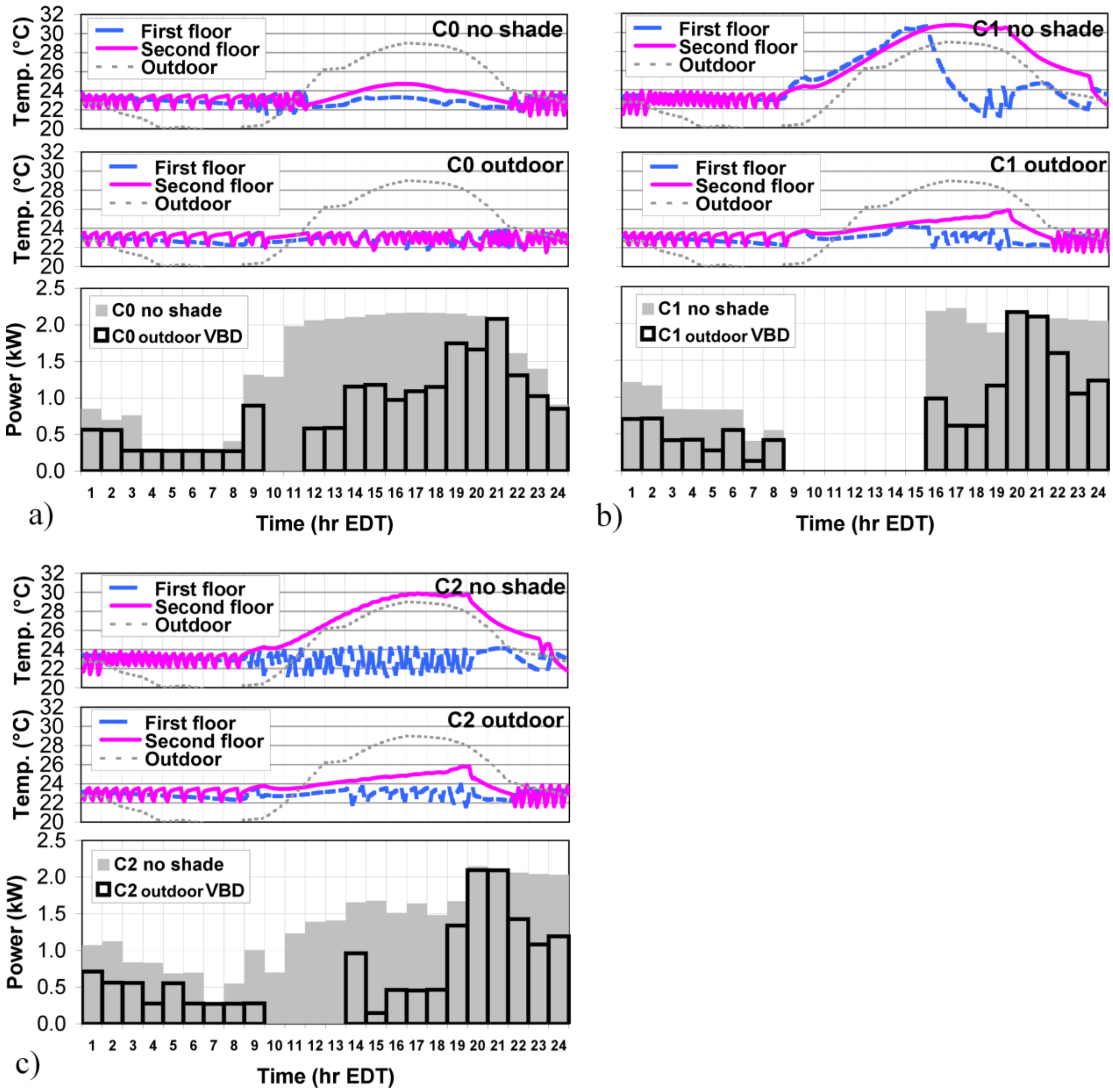


Figure 4: Temperatures and hourly averaged cooling power for unshaded vs. outdoor Venetian blind cases subject to the three zoned control scenarios a) C0, b) C1 and c) C2.

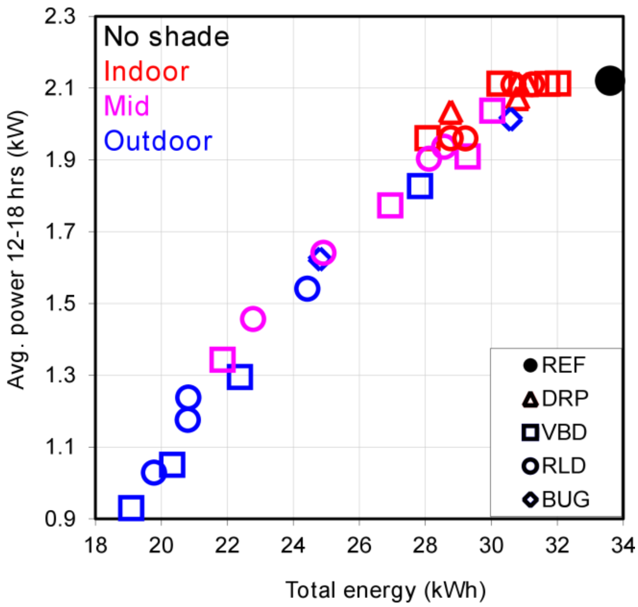


Figure 5: Total cooling energy vs. averaged power between 12:00-18:00 hours for the set of shading configurations and zoned control scenario C0 (shade layer position indicated by colour).

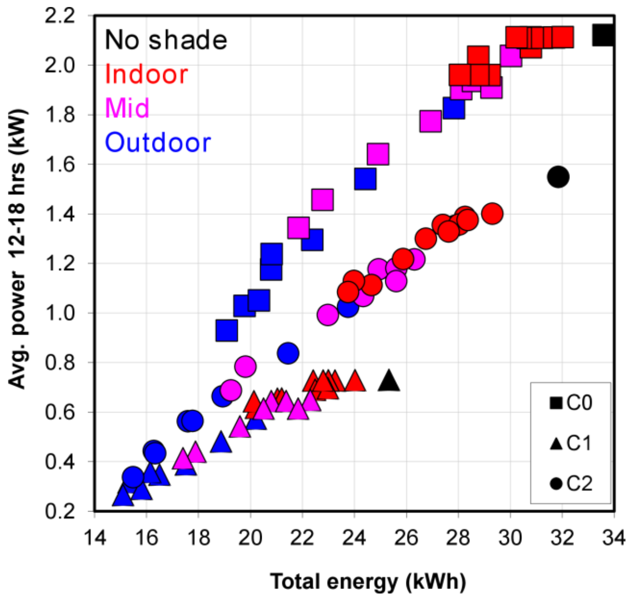
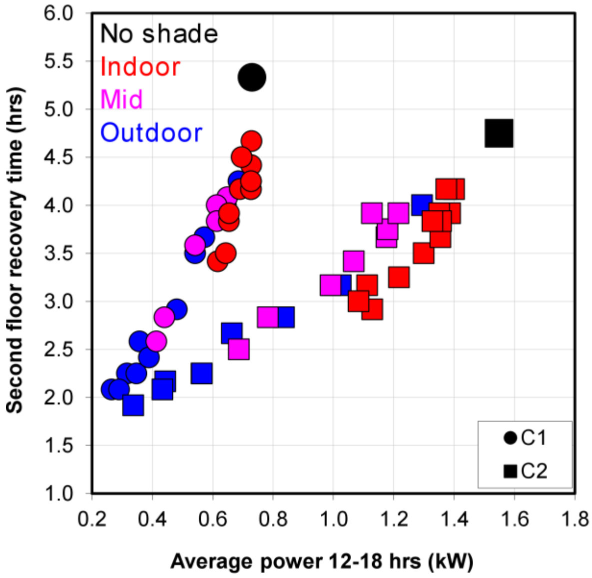
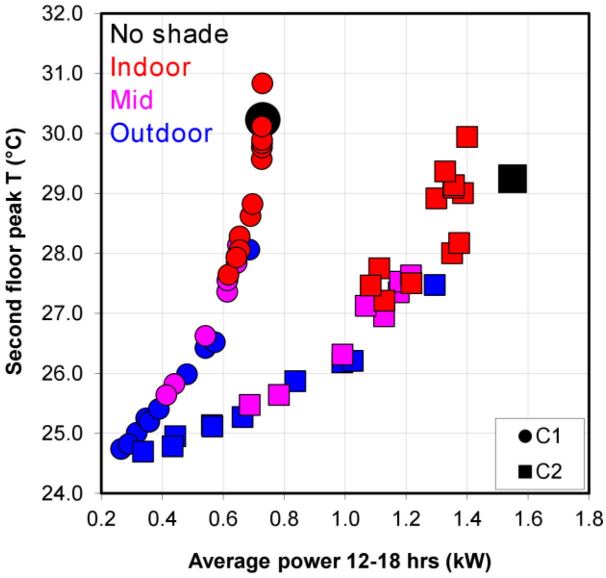


Figure 6: Total cooling energy vs. averaged power between 12:00-18:00 hours for the set of shading configurations and zoned control scenarios C0, C1 and C2 (shade layer position indicated by marker colour).



a)



b)

Figure 7: Averaged power between 12:00-18:00 hours vs. a) second floor recovery time and b) second floor peak temperature for zoned control scenarios C1 and C2 (shade layer position indicated by marker colour).

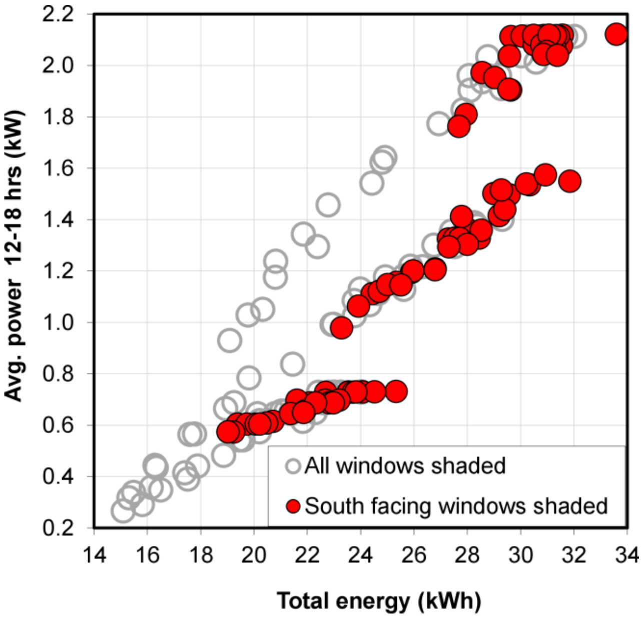


Figure 8: Total cooling energy vs. averaged power between 12:00-18:00 hours showing all results for the completely shaded façade (unfilled markers) and the partially shaded cases with shading on the south facing windows only (filled markers).

4 Discussion

In the reference scenario (C0 no shade) shown in Figure 4a, no peak mitigation strategies are employed. All windows are unshaded and the thermostats are set to maintain both first and second floor zones at 23°C. As a result the cooling system operates continuously for the entire afternoon and early evening hours, the capacity of which is inadequate to meet the total sensible and latent heat loads consisting of the solar gain through windows, occupant gains and envelope heat and infiltration gains. Continuous operation of the cooling system is indicated by the smooth temperature profiles peaking above the thermostat setting as well as the flat top profile of the hourly averaged power throughout this period. Hence without any peak mitigation the cooling system is undersized resulting in the indoor temperatures above the thermostat setpoints.

The simulation results shown in Figures 4-8 suggest that the addition of active zone control cooling scenarios in combination with passive window shading can result in a large reduction of both total cooling energy and peak electricity demand. The effect of window shading alone is discussed first, followed by the addition of zoned control strategies C1 and C2.

Concentrating on Figure 5, the impact of various shading configurations on the total energy and peak cooling power is shown for zoned cooling scenario C0. Here, all windows are shaded with the respective shading types and shading layer placements shown in Table 2. Relative to the unshaded case (solid black circle), the spread of the results is quite large and the reduction in total energy and peak power are well correlated. Moreover, the general trend indicates that outdoor shading configurations have a deeper impact on the reductions, followed by between-pane (mid) configurations, followed by indoor shade configurations. There is also some overlap between the three shade placement groups which can be attributed to the variety of shade colours and fabric openness. For instance, a dark roller blind with relatively large openness can result in larger total solar gain than a light indoor blind with small openness. Similarly, a venetian blind with partially open slats will admit more solar transmitted flux into the space regardless of it's placement within the window assembly. This is also the case for insect screens, which, although placed on the outdoor side, admit a large portion of solar transmitted flux due to their large mesh spacing. The results demonstrate that outdoor Venetian blinds with closed slats and outdoor roller blinds with a closed mesh fabric are most effective in rejecting solar gain. The indoor shading configurations, on the other hand, are clustered relatively closely to the reference unshaded case, thus showing small reductions in cooling energy and peak power. The spread in results is again due to the shade colours and fabric openness, with lighter closed mesh fabrics accounting for larger reductions.

The placement of the shading layer ultimately determines the proportion of absorbed solar energy that is transferred to the indoor space. This is the so called inward-flowing fraction of solar gain. The total solar gain is then composed of the transmitted solar energy as well as the longwave radiative and convective fluxes of the inward-flowing fraction. In general, outdoor shades are able to reject most of the solar absorbed portion to the outdoor environment, whereas an indoor shade will convert a large fraction of the transmitted solar flux to convective heat flux exchanged with the room air. As will be shown later, an indoor shade can exacerbate peak indoor temperatures as the shade layer has virtually no heat storage capacity. It is also worth mentioning that, although not considered in the present study, the effect of awnings is similar to the impact of outdoor blinds, depending on the extent to which the awning obstructs the direct and diffuse solar fluxes.

The observed decrease of total cooling energy and peak power associated with the set of shading configurations can be even more pronounced when combined with the zoned control strategies that take advantage of the occupancy schedules according to scenarios C1 and C2. Figure 6 shows the expanded set of simulation case results that includes C1 and C2 control scenarios. Three distinct, well correlated groupings can be seen in the total energy vs. peak power plot, each corresponding to the zoned control strategy employed. Within each grouping is the set of shading configurations with trends similar to those discussed above in

Figure 5. Of interest is also the impact of the control strategies alone, without any use of shading. A 26% reduction in total cooling energy and a 64% reduction in peak cooling power is achieved by employing the zoned control scenario C1, in which cooling is turned off to both zones for most of the day. Even greater savings are possible with the outdoor shading configurations, reaching a maximum of 55% reduction in total cooling energy and 88% reduction in peak cooling power. Similar savings are obtained with scenario C2, in which the first floor is still occupied during the day, but are only realized in combination with the closed outdoor shading configurations. The reader is referred to Figure 4 for the hourly temperature and cooling power profiles of the best case closed slat outdoor Venetian blind cases in contrast to the reference unshaded cases.

Although the zoned control scenarios C1 and C2 offer significant savings in total cooling energy and peak power, an evident trade-off is the evening recovery time associated with the time that it takes for the zone temperature to return to the setpoint value once cooling resumes after the free-float period. In scenario C1, the recovery time of the first floor is short because all of the cooling capacity is directed to that zone at 15:00, while the second floor is free floating. The recovery time of the second floor is generally longer and may result in uncomfortable conditions in late evening, especially because the second floor recovery coincides with evening gains associated with appliance use, thus limiting the cooling capacity available to the second floor. The temperature profiles in Figure 4 of the reference unshaded cases for C1 and C2 control scenarios illustrate this trade-off.

Figure 7 quantifies the recovery time vs. the peak cooling power for the set of shading configurations combined with C1 and C2 control scenarios. Closely linked is the maximum temperature reached on the second floor during peak hours, for it is correlated with the accumulated heat and thus extent of the recovery time in the evening. These results suggest that it is possible to achieve both a large reduction in peak power while maintaining the recovery time to about 2 hours with the more aggressive outdoor shading configurations. The rise in second floor temperatures for these cases is only about 2°C, whereas in the indoor shade configurations as well as the reference unshaded cases, the temperature can rise to 30°C or so, placing a heavy demand on the evening cooling period. It is interesting to note that peak temperatures are highest with the dark closed fabric indoor blind cases as is shown in Figure 7b. This is the result of the absorbed solar flux on the indoor blind. The blind is effectively immersed in the room air and is therefore convectively coupled to the conditioned space. Moreover, because the indoor blind has very little thermal mass, much of the absorbed solar flux is readily converted to convective heat gain without the benefit of any storage effects (e.g., interior walls, floors and furniture) which help to buffer the transmitted solar gain.

Lastly, it is worthwhile examining the effect of partial shading; namely, shading only the south facing windows. The glazing distribution of the CCHT house model is such that the south facing windows account for roughly two thirds of the total transmitted solar flux in the unshaded case for the given location and imposed weather data used in the model. Of the remaining glazing area, the east facing windows admit a significant amount of solar flux in the morning hours and the north facing windows admit mostly diffuse solar flux throughout the day. With only the south facing windows shaded, one would then expect the resulting savings in total cooling energy and peak power to amount to about two thirds of the savings in the already discussed cases for which all of the windows are shaded. However, Figure 8 shows that results fall short of this rough estimate. The maximum reductions for the C1 and C2 control scenarios amount to about 50% of those obtained in the fully shaded cases. The savings are even less for the C0 cases. In the C1 and C2 scenario results, it is likely that the free-floating daytime periods followed by the evening recovery period result in a more complicated energy balance throughout the day, thus invalidating the use of a simple area-based estimate. Dissipation of the accumulated heat in the second floor zone aided by infiltration during the evening recovery period could be significant, for instance. Similarly, the results in the C0 control scenario would look quite different if the total cooling capacity was sufficiently large to cope with the C0 unshaded scenario, for which the 2 ton unit was shown to be undersized. The larger capacity unit would result in greater total cooling energy and peak power, thus bringing the C0 south-only shading results closer in line with the C1 and C2 south-only results, in relative terms.

5 Conclusions

Based on results from the parametric simulation case study of the CCHT house model, the combination of zoned control cooling scenarios and window shading can result in large cooling energy and peak power reductions, while maintaining low indoor temperatures during free floating periods and thus short (~2-2.5 hour) recovery periods during the peak occupancy gain evening hours.

In the most aggressive peak mitigation cases with outdoor closed shades on all windows and zoned control scenario C1, a 55% reduction in total cooling energy and an 88% reduction in peak cooling power were achieved. Although the zoned control strategies alone can yield significant peak power reductions (65% and 28% for C1 and C2 relative to C0, respectively), the second floor peak temperatures (~30°C) and recovery periods (~5 hours) limit the practical application of such an approach on its own. It is only with mid or outdoor closed shade configurations that very large reductions can be realized without compromising occupant comfort during the evening recovery period. The use of indoor shades can also yield moderate savings (up to 22% and 25% reductions in total energy and up to 14% and 29% reductions in peak power, relative to the unshaded C1 and C2 cases, respectively) but the approach suffers from the convective coupling of the shade with the indoor air due to the absorbed portion of the solar gain. As a result, higher second floor peak temperatures and longer recovery times are observed relative to the mid and outdoor shading configurations.

6 References

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