The zero-peak house: full-scale experiments and demonstration

Newsham, Guy R.; Galasiu, Anca D.; Armstrong, Marianne M.; Beausoleil-Morrison, Ian; Szadkowski, Frank; Sager, Jeremy M.; Pietila, Andrea J.; Rowlands, Ian H.

Publisher's version / Version de l'éditeur:
https://doi.org/10.1016/j.enbuild.2013.05.004
Energy and Buildings, 64, pp. 483-492, 2013-09-01

The Zero-Peak House: Full-scale Experiments and Demonstration

Guy R. Newsham[a], Anca D. Galasiu[a], Marianne M. Armstrong[a], Ian Beausoleil-Morrison[b], Frank Szadkowski[c], Jeremy M. Sager[c], Andrea J. Pietila[b], Ian H. Rowlands[d]

[a]National Research Council Canada, 1200 Montreal Road (M24), Ottawa, Ontario, K1A 0R6, Canada

[b]Carleton University, Mechanical and Aerospace Engineering, 1125 Colonel By Drive, Ottawa, Ontario, K1S 5B6, Canada

[c]Natural Resources Canada, 580 Booth Street, Ottawa, Ontario, K1A 0E4, Canada

[d]University of Waterloo, Faculty of Environment, 200 University Avenue West, Waterloo, Ontario, N2L 3G1, Canada

Corresponding Author: Guy R. Newsham; t: (613) 993-9607; f: (613) 954-3733; e: guy.newsham@nrc-cnrc.gc.ca

Abstract

Houses represent a substantial fraction of the summer peak electrical load, and therefore measures to reduce peak demand at the household level may be valuable in stabilizing the grid and lowering peak costs. We conducted studies in geometrically-identical, side-by-side full-scale detached houses. One house was operated in a conventional manner and provided a typical reference case. In the other house we applied a variety of measures designed to reduce or shift load from peak periods. Our results demonstrated that a combination of practical operational modifications (air-conditioner cycling, doing laundry later in the evening) and commercially-available technology (exterior shading, modest PV array, energy-efficient lighting) was able to dramatically reduce (in some cases to zero) the peak electrical demand from the grid on the hottest days of the year.

Keywords

summer, electricity, peak demand, Canada, house, shading, air conditioning, PV

Highlights

- Peak grid electrical demand of a detached house was reduced to zero on hot days

- The combination of measures might be unappealing due to inconvenience or cost
- Other combinations may reduce peak load substantially at acceptable cost
- Incentives for external shading and other measures should be considered

1. Introduction

Many jurisdictions in North America experience a peak demand for electricity on hot summer afternoons, primarily due to rising air-conditioning (AC) load[1]. In such situations utilities must import additional energy (often at a cost premium), deploy peak period generators, or reduce demand. There might not be the ability to build additional generation, transmission, and distribution fast enough to accommodate projected demand growth, and thus the frequency of peak demand problems is expected to grow [1]. Indeed, in Ontario, Canada, the peak demand for electricity is growing faster than total electricity use [2].

As a result, there is growing interest in partly addressing this issue on the demand side [2-3], that is by eliminating some electricity use on peak, or shifting it to non-peak times. Methods to facilitate this are being explored in all building types, including residential buildings.

This paper reports on the final phase of a project exploring whether the grid electricity use of a single-family detached house with AC in a summer peaking region could be reduced to zero during periods of high systemwide demand. There are four general approaches to reducing peak load:

> Passive design – designing the house's infrastructure to reduce electricity demand. This might include fixed shading such as overhangs, glazing type and positioning, thermal mass, reflective roofing, and low-power lighting and appliances.
>
> Behavioural modification – information and incentives for occupants to use less power at peak times. This might include pricing regimes [4], and feedback on energy use [5].
>
> Automatic controls – systems that respond to interior or exterior climate conditions, or utility signals and actuate to reduce electricity use without direct, immediate intervention by the occupants. This might include direct load control of AC, water heaters or other loads by the utility [6], or motorized blinds.

[1] Some cold climate regions are winter-peaking. Winter peaks tend to occur in early morning and in the evening, when heating-related loads are added to increased lighting loads and residential activity loads. The focus of this paper, however, is summer peaks.

Local generation and storage – for residual loads after the reduction methods above, the use of prevailing grid-supplied electricity can be displaced by local sources. This might include rooftop-mounted photovoltaics (PV), and battery storage of off-peak power (either PV- or grid-supplied).

Achieving a zero-peak house (ZPH) will likely require elements from all four of these categories.

Research on ZPHs has been limited to date. Buntine et al. [7] used simulation to examine the effect of various modifications to a two-storey detached house in the hot, dry climate of southern California, for which the baseline peak hourly load on the highest-demand day was 4.9 kW[2]. A combination of more efficient AC, high-performance glazing, additional envelope insulation, fixed external shading (awnings), fluorescent lighting, and additional thermal mass reduced this peak by around 50 %. An optimally-oriented PV array of around 4 kW could then reduce the load on the grid to zero during peak hours. The authors suggested that this package of measures would not be cost-effective to the homeowner due to the high prevailing costs of PV installation ($8/W), but would be cost-effective if PV costs were reduced to around $5/W.

Christian [8] reported on peak load measurements made on two-storey houses that had been explicitly designed as low-energy houses in the hot, humid climate of Tennessee. Findings were referenced to a typical house in the same climate, with a peak load of around 6 kW on summer days. The author showed that with a combination of measures load could be reduced to zero during peak hours while maintaining comfortable interior conditions. These measures included energy-efficient design (high-efficiency AC, high-performance glazing, additional envelope insulation, fluorescent lighting, solar water heating), a pre-cooling thermostat strategy, a 2.2 kW PV array, and 11 kWh of battery storage.

Kerr [9] studied the peak load in low-energy houses in the hot, dry climate of Sacramento, California. Findings were referenced to a typical house in the same climate, with a peak load of around 2.9 kW on summer days. A combination of energy-efficient design (high-efficiency AC, high-performance glazing, additional envelope insulation and anti-infiltration measures, fluorescent lighting, low-energy appliances, tankless water heating) and an optimally-oriented PV array of around 2 kW reduced the load

[2] Typically, hourly values are presented. Therefore, the load is the average load over the hour, and not the maximum instantaneous load, or the load averaged over a sub-hourly timeframe; the magnitude of load values depends greatly upon the averaging period. For hourly data, for example, the units are more accurately kWh/h, but we use kW to be consistent with the original publications and across publications.

on the grid to a maximum of 0.75 kW during peak hours. This information was used in the design of new houses, with the explicit goal of achieving a ZPH. This design included high-thermal mass walls, night-time ventilation technology, a pre-cooling thermostat strategy, and shading overhangs.

Hammon [10] used simulation to examine the effect of various modifications to a single-storey detached house in Sacramento, California. The baseline house had the same energy-efficient design as the house described by Kerr [9], for which the modelled peak hourly load on the prototypical high-demand day was 2.7 kW. A combination of tile floors, high-insulation and high thermal mass walls and a high-efficiency AC unit cut this peak by about 50 %. A 2 kW PV array reduced demand from the grid below zero from 9am-4pm. The author further described a 6.2 kWh battery storage system charged by the PV system to flatten load to 0.55 kW over the entire day.

Pietila [11] and Pietila et al. [12] used simulation to examine the effect of various modifications to a two-storey detached house in the hot, humid summertime climate of southern Ontario. This study was designed, in part, to help select plausible retrofit options for the existing, real house described in the main body of this paper. The author identified the following as being particularly effective in reducing peak load: external window blinds, pre-cooling, AC cycling, high-efficiency AC, opening windows when outdoor conditions allowed, and assuming behavioural shifts in when major appliances are used. The most effective combinations of these strategies reduced modelled peak load from around 6.4 kW to 2.2 kW on the worst-case day. Further, grid demand could be reduced to zero during the peak hours of the 10 hottest summer days with the use of a 1.6 kW PV array and 3.8 kWh of battery storage.

Note that research on net-zero energy or very low energy houses is more common. In such houses the goals often include reducing net electrical energy draw from the grid to zero when summed over a whole year, and the strategies employed are often very similar to those used in ZPHs. While the aim is not explicitly to reduce peak electricity draw to zero during specific high-usage hours, the result is often a substantial reduction in peak electricity use, as demonstrated by Parker [13].

In the research reported in this paper we take the study of ZPHs further by applying a combination of load-reduction measures to an existing conventional house. Note that there is no standard definition of what constitutes a ZPH. First, one must define the peak period, which differs from region to region, and whether one is considering the peak hours on all summer days, on only specific "critical peak" days, or some other period. Second, should the grid power draw be reduced to zero for the entire set of peak hours under consideration, or only a subset of hours, or should one consider a net-zero draw during the peak period? In this paper we used a relatively forgiving criterion, and considered the ZPH target to be achieved if the grid power draw was reduced to zero during at least one hour of the utility-defined peak period, and substantially reduced for other hours of the peak period during our testing days (without recourse to electrical storage).

2. Methods & Procedures

The study took place at the Canadian Center for Housing Technology (CCHT) located in Ottawa, Ontario. The facility features two side-by-side twin-houses as shown in Figure 1 [14]. The house on the right is used as a baseline (Reference House), while the house on the left is used for testing various energy efficiency measures (Test House). Both houses are two-storeys, 210 m^2 floor area (unfinished basement not included) and replicate a popular local design. They were built to the R-2000 standard [15], using conventional regional construction technologies. Each house features 26 double-glazed, argon-filled, low-e windows, U-value = 1.65 W/m^2K, SHGC = 0.72, and a north-facing glazed patio door. The windows are distributed as follows: 11 south-facing (10.22 m^2); 12 north-facing (10.97 m^2); one west-facing (1.30 m^2) and 2 east-facing (1.65 m^2). Both houses were equipped with a standard set of appliances for North American homes. The houses had a simulated occupancy system that reproduced the daily water draws and electrical loads of a family of four. The internal heat gains from the occupants were also simulated. The houses employed high-efficiency gas furnaces for heating, continuous flow heat recovery ventilators and programmable thermostats located in the central hallway on the main floor. The set point temperature for cooling was fixed at 24^{o}C.

The houses were highly-instrumented: individual appliance energy use, interior temperature and humidity at multiple locations, and exterior climate data were all recorded at five-minute intervals.

We applied various combinations of measures to the Test House, with the goal of reducing peak electrical demand. These measures were as follows:

- Normally, the CCHT houses use incandescent lighting throughout, we replaced those in the Test House with compact fluorescent lamps.
- The standard daily schedule was use of the clothes washer from 17:00-18:00 and of the dryer from 19:00-19:25; in the Test House this was changed to 20:00-21:00 and 21:00-21:25 respectively, to simulate occupants motivated to shift use of these major appliances outside of peak hours.

- The forced air supply registers to the basement of the Test House were closed, to avoid using mechanically-chilled air to cool an already cool (and unfinished) space.
- The AC unit in the Test House was forced into a cycling mode between 15:00-19:00. During this period the AC compressor was only allowed to run for 15 minutes at a time before being shut off for 15 minutes, even if the set point had not been reached (the furnace fan continued to run at low speed when the compressor was not running). This mimics the residential peaksaver® program in Ontario [16].
- The normal window shading in the CCHT houses is horizontal internal venetian blinds at all times. We tried two variants of window shading in the Test House. One option was external roller blinds on all windows, closed at all times (Figure 2). With the blinds we had, it was impractical to change their position regularly, as would be possible with motorized blinds that responded to internal or external conditions. It is unlikely that householders would keep blinds closed continuously, therefore our implementation can be considered a best case for AC reduction. A second option was raising the external blinds, and closing the internal venetian blinds; the blinds on the south and west wall were closed at all times (Figure 2), whereas those on the north were left in a horizontal position. Note that dummy boxes were added above the windows on the exterior of the Reference House to account for the shading effect of the exterior blind valences on the Test House.
- Normally, the windows of the CCHT houses are closed at all times. For the Test House, we opened the windows on the upper floor (Figure 2) between 20:00-08:00.
- PV panels were installed on the roof of the CCHT Infocentre, next to the two test houses (Figure 2). The production of these panels was recorded and we applied this to reduce the Test House grid load, as if they had been mounted and connected directly to the Test House. The array consisted of eight 1.34 m^2 modules with a rated efficiency of 8%, facing due south at 34.1° from horizontal, each with nominal peak power when new of 165 W. However, these modules were not maintained and have degraded over time (they were first installed in 2003), such that their maximum *in situ* production during the study was around 50 W per module, equivalent to a measured efficiency of about 4%.

The timing of these measures was chosen to reduce house electricity use in hours that comprised the utility peak periods. In summer weekdays in Ontario the tariff periods were defined as follows: on-peak = 11am-5pm (Hydro Ottawa commodity rate 10.7 cents/kWh); mid-peak=7am-11am & 5pm-7pm (8.9

cents/kWh); off-peak=7pm-7am (5.9 cents/kWh). However, we also considered the typical residential peak, which tends to occur later than the system peak.

Table 1 shows which measures were applied on which days, with summary weather information.

3. Results

3.1 Potential Modifications to the Raw Data

Before presenting our results, we first consider several modifications that may be made to the raw data we collected from the houses. These modifications are always optional, and we present results with and without them, but we submit that they enhance the accuracy and applicability of the data.

3.1.1 Inherent differences between the CCHT houses

Figure 3 shows the daily electrical use of the AC system for 24 days (June 2-7; June 9-23; August 5-7, 2011) when no peak load reduction measures were applied and the houses were nominally identical (baseline days). The Reference House used around 7.5% more energy than the Test House, on average. We then chose the six of these baseline days that were closest in climate to the set of days on which our measures were applied, and Figure 4 shows the mean hourly AC use on these days for the Reference and Test House. It is clear that the differences between the houses are not uniformly distributed across the hours of the day, which might be due to small differences in shading from external obstructions, and small differences in refrigerant charge between nominally identical AC units.

We apply an optional correction for this inherent difference between the houses. We took the mean difference between the houses on these six benchmark days for each of the utility billing periods and used this to “correct” the Reference House data on days when we applied peak reduction measures, this percentage correction is also shown in Figure 4 (we derived similar corrections for fan electricity use, and for total use). This correction represents our best estimate of how the Test House would have performed on these days had no measures been applied. The effect of this is to make our savings estimates during peak hours more conservative.

3.1.2 Potential adjustment for furnace fan

The furnace fans in the CCHT houses used split capacitor (PSC) motors. Newer furnaces use electronically commutated motors (ECM), also known as brushless DC motors. Generally, furnace fan motors operate at higher speeds than necessary to provide continuous ventilation to the house. ECM motors can be programmed to lower speeds than PSC motors, and are more efficient at these lower speeds, leading to energy savings. An earlier study at the CCHT houses [17] compared the performance of these two fan types, and the result is shown in Figure 5. At high speed the two motors are comparable, however, at low speed the ECM used substantially less electricity.

As an optional modification, we estimated the reduction in electricity use had we been able to replace the PSC motor with an ECM motor as one of our peak reduction measures in the Test House. Using the information in Figure 5, we scanned the fan power in the raw data file and created an alternative fan power in which raw values of <=350 W were replaced with 31.6 W (low power mode), and raw values of >350 W were replaced with 508 W (high power mode). Note, we did not attempt to account for the secondary effect that the reduced dissipated heat from the ECM motor would have on the AC load, and therefore our correction could be considered to be conservative.

3.1.3 Potential adjustment for AC efficiency

The AC units at the CCHT houses were 2 ton, 13 SEER (Seasonal Energy Efficiency Ratio). The higher the SEER number, the more efficient is the AC unit. SEER may be related to other measures of AC efficiency EER (Energy Efficiency Ratio) and COP (Coefficient of Performance), by the following equations [18]:

$$EER = -0.02 \bullet SEER^2 + 1.12 \bullet SEER \qquad \{1\}$$

$$EER = 3.412 \bullet COP \qquad \{2\}$$

For example, a SEER of 13 is approximately equivalent to an EER of 11.2, and a COP of 3.3.

We estimated the reduction in electricity use for cooling had we been able to replace the AC unit in the Test House with a unit of higher SEER (up to 26). We used Eqs. 1 and 2 to estimate the COP for higher SEER units, and then multiplied the actual energy use of the 13 SEER unit in the raw data by the appropriate ratio. Again, this optional modification is approximate, and ignores any secondary effects, such as those on fan energy use, and again may be considered conservative.

3.1.4 Extrapolation to a more efficient/larger PV system

The PV system at the CCHT was modest in size and had a poor effective efficiency, resulting in a peak output of ~400 W during the period of our measurements. A more typical, new installation would feature a higher efficiency (12 % is not unusual, and there are commercially-available panels at >20%

[19]), and could easily have a larger area on a residential roof. As an optional modification, we multiplied the actual output of our PV array by a factor of up to 4, to estimate the effect of a replacement PV array available to the Test House with a higher, but still reasonable, output. The maximum nominal peak output of our optional modification was thus 1.6 kW, which was the size of unit suggested by Pietila's [11] simulation results for Ontario.

3.2 Effectiveness of the Measures in Reducing Peak Load

We applied the peak load reduction measures in various combinations. Most measures were applied on all days, but we did vary measures related to windows (shading, opening) to explore the relative contributions of some individual measures. A summary of these combinations, and the days on which they were applied, is shown in Table 1.

We began with the combination of measures we expected to be most effective, in which the window treatment was exterior roller blinds. We were lucky that the first day available to us turned out to be the hottest day of the summer, and the only residential peaksaver® program event day of 2011. The various total load profiles (actual measured data and selected optional modifications) are shown in Figure 6. Note that in this graph we show the energy generation from the PV array as a negative load, and we show both the actual measured generation (PVx1) and the estimated generation for the largest replacement array we considered (PVx4). We show both the Reference House actual measured load (dark red line), and the derived corrected load (light blue line). The next line below that is the actual load of the Test House with all load reduction measures applied (green line) (the difference between this line and the (light blue) line above it comprises the savings summarized in Table 1). Below that is the estimated effect of replacing the Test House fan PSC motor with an ECM motor (pink line). Below that is the estimated effect of replacing the Test House AC unit with a 21 SEER unit (orange line), the highest SEER we judged reasonable from a cost perspective. This effect is relatively small during peak periods, which may be expected given that the other measures greatly reduce the time that the AC is running. Finally, we show two lines which use a combination of load reduction measures and offsetting PV generation to reduce the Test House load to zero for at least some of the time during the utility peak period. In one case we used the Test House equipment as is, and applied the maximum PV modification factor (dark blue line). In the other case, we can use a smaller (1.2 kW) PV array, provided that the Test House AC equipment efficiency is improved via an ECM motor and 17 SEER compressor (dashed red line).

Table 1 summarizes the savings (difference between the corrected use of the Reference House, and the actual use of Test House with load reduction measures as implemented, and with no offsetting PV generation) for each of the experimental days. Though there were climatic variations over the five days on which this combination of measures were applied, the savings during on-peak were consistently around 50%[3].

Note that although the total load with the measures is considerably reduced during on-peak and mid-peak periods, it does rise substantially by 10 pm. The primary reason for this is the shift in clothes washer and dryer loads to later hours in the Test House.

On July 26th we transitioned to a new scenario, the drawn external blinds were removed and we reverted to internal blinds down but horizontal in the Test House. Figure 7 shows the hourly load profiles for July 28th, which had high temperatures and a clear sky. Although outside temperature peaked at 32.6 ^{o}C, it was still considerably lower than on July 21st, and total electrical load was also reduced. The savings with the base set of measures were quite small during the on-peak period, which emphasizes the importance of external shading in the prior scenario. Savings in the evening mid-peak period were substantial, primarily due to the shifting of laundry-related loads, and the reduction of lighting loads. Nevertheless, it was not possible to realize the ZPH target.

In the next scenario the internal blinds were closed in the Test House. Figure 8 shows the hourly load profiles for August 1st, which had high temperatures and a clear sky. Closing the internal blinds improved the on-peak savings somewhat, but the savings were still small compared to the closed external blind scenario, and it was not possible to realize the ZPH target.

In the final scenario the upper floor windows of the Test House were opened overnight (minimum overnight temperature was 16.9 ^{o}C, recorded at 6 am). Figure 9 shows the hourly load profiles for August 3rd, which had milder summer conditions compared to the other example days. Opening the windows reduced morning temperatures in the Test House, which delayed the start of AC use from 8 am to noon. As a consequence, and in combination with the other measures and modifications, it was

[3] The electricity consumption on individual circuits was measured with Elster Alpha Plus meters which had a stated bias error of 0.2% of reading. The predicted savings were calculated by subtracting the measured electrical consumption from a given Test House circuit from the measured value in the Reference House. Furthermore, the measurements from the Reference House were corrected to account for inherent differences between the houses, which further propagated measurement uncertainty. By combining all possible sources of error and by propagating these through a root-sum-square approach, the overall bias error in deriving the energy savings from the primary measurements was ~1% of the predicted savings.

possible to meet the ZPH target in the morning mid-peak and early on-peak periods. The efficacy of night-time ventilation to offset residential cooling loads in hot climates was demonstrated by Santamouris et al. [20].

3.3 Interior Thermal Conditions

Although reducing peak load is important for a utility, it is unlikely to be embraced by householders if the necessary measures create very uncomfortable interior conditions, even if this lasts only a few hours. For brevity, we focus on the conditions on July 21st-25th, when we used external blinds and achieved the greatest load reductions on the hottest days, and compare these to data for August 5th-7th, benchmarking days when the houses were nominally identical. In Figure 10 we plot humidity vs. air temperature values for the Test and Reference Houses, on each floor of the house; each symbol represents an hour during this period. Overlaid on the chart are example thermal comfort zones for two versions of the ANSI/ASHRAE Standard 55 [21-22]. Combinations of humidity and temperature within these zones would be predicted to deliver acceptable thermal comfort for a large majority of occupants ($-0.5 \leq PMV \leq 0.5$) according to Fanger's thermal comfort model [23]. Calculation of these zones assume radiant temperature equal to air temperature, a typical summer clothing insulation level of 0.5 clo, and low air speeds[4]. The only difference between these zones is that the 2010 version assumes a metabolic rate of 1.1 met (seated relaxed/sedentary), and the 1992 version assumes 1.2 met (sedentary). Different assumptions for these variables would produce different comfort zones on the chart.

Focussing on the 1st floor, and by considering the pre-existing differences established on benchmarking days, the data suggests that the combined peak reduction measures led to an elevation of air temperature of 0.5 – 1 ^{o}C, and an increase in the humidity of ~15%. In this regard, we see that conditions in the Reference House would be considered a little on the cool side for much of the time, and that the increase in temperature and humidity resulting from the peak reduction measures actually improved thermal conditions. However, this interpretation rests on several assumptions, and it is possible that the higher humidity in the Test House would be more unwelcome in our context than Fanger's comfort equation suggests. Nevertheless, we propose that the thermal conditions created by peak reduction measures would be tolerable to many occupants. Field studies of utility residential AC cycling programs support the suggestion that intolerable thermal discomfort in unlikely in such scenarios. For example, Kempton et al. [25] note that participants in a program in New Jersey, in which

[4] although we did not measure air velocity in this research, measurements in the CCHT for a prior shading only project [24], indicated air velocities around 0.05 ms^{-1}.

AC units were cycled off 50% of the time for 5 hours on hot summer afternoons, reported an average temperature increase of only 0.3 ^{o}C. Further, the number of participants saying they did not have enough cooling increased from 7% on equivalently hot non-cycling days to 15% on cycling days.

4. Discussion

The data from the full-scale house experiments show that we can achieve the ZPH target with a careful selection of retrofit measures in a typical Canadian single-family house. Although the relative contributions of each measure are difficult to ascertain exactly given the climatic variations from day-to-day and the fact that most measures were not implemented independently, it is clear that the external blinds contributed more to savings than all of the other measures combined. Table 1 shows that the combination of CFL lamps, delayed laundry schedule, closed basement registers, AC cycling, and horizontal internal blinds reduced AC use on-peak by ~20 %; closing the internal blinds increased savings to ~28%. Replacing the internal blinds with closed external blinds raised the on-peak AC savings to ~70 %. We may also reasonably infer that the external blinds also served to offset the internal temperature rise resulting from AC cycling.

Our implementation of external blinds was effective and simple, but crude: the blinds were lowered on all windows 24 hours per day. It is unlikely that occupants of a real house would tolerate this for peak load reduction. Pietila's [11] simulations included motorized external blinds triggered by an internal or external temperature criterion or a solar radiation criterion. This meant that the blind was only deployed for a minority of hours when cooling needs were highest, such that the peak load reduction effect was largely preserved in a manner that would likely be more acceptable to householders. It is also possible that manually controlled blinds would not have to be deployed at all hours or on all windows to realize most of the peak load reduction effect, but it was not practical for us to explore this. Fixed awnings or overhangs might provide some of the load reduction benefit in a cheaper and more acceptable manner. The simulation studies described in Pietila [11] and Pietila et al. [12] did include these options, and an earlier shading study at the CCHT [26] also measured their effect. In Pietila's studies a set of measures similar to those used in our study was combined with various shading options. In one case the shading option was awnings in addition to overhangs and trees, and in another case the shading option was actuated external blinds. In terms of total summer on-peak energy use, the former combination performed only marginally worse than the latter. On the summer days with the highest solar radiation, Gusdorf et al.'s results showed that awnings alone reduced total daily AC and furnace fan electrical energy use by ~15%, and lowered internal temperatures by ~1^{o}C.

The fact that the ZPH target could be reached on July 21st, the hottest day of the year, combining an outside air temperature of 38.0 ^{o}C with a humidity of 41 %, suggests that zero-peak could be achieved on any sunny summer day in southern Ontario. Further, these conditions are also representative of climates in many other places, which suggests that the measures we employed have wider applicability.

All of the measures we implemented, and the optional modifications, were commercially-available technologies or easily implemented behaviours. The exterior blinds we used were relatively expensive, and while exterior blinds (or other exterior shading devices) are rare in North America, they are common elsewhere. PV arrays are also rare, but growing in popularity with the encouragement of green energy incentives and the rapid fall in prices. The array we used was relatively small compared to many residential systems currently installed. We did not include electrical storage in our measures, but it could complement or replace the PV array for this application. PV energy generated outside of peak hours could be diverted to peak periods when immediate generation is inadequate, or cheaper off-peak grid electricity could be deployed similarly[5]. Indeed, adding more and more PV/electrical storage allows zero peak performance to be achieved for more hours on more days, but with diminishing returns, a topic explored in more detail in Pietila [11] and Pietila et al. [12][6].

The combination of measures to get to zero load during peak periods may present a considerable cost barrier. Nevertheless, a cheaper combination can still substantially reduce peak load, and this would have great value to utilities if applied broadly. This may be facilitated by offering homeowners financial or other incentives to adopt these strategies. Incentives related to some of our measures do exist in some locations, although they are not always focussed on, and valued with respect to, peak reduction. Many utilities (or related bodies), offer incentives for AC upgrades, PV installation and AC cycling, but incentives for exterior shading are rarer [28].

Even if our measures are focussed on peak load reduction, some combinations also reduce overall energy use (rather than just displacing it). For example, simulations conducted by Pietila [11] suggested

---

[5] Note that in Ontario, where this study was conducted, there is a generous feed-in-tariff (FIT) program for residential PV. The consequence is that it is much more lucrative for a householder to sell PV power to the grid when it is generated than to use it locally to offset their own load. Thus in Ontario we can imagine rooftop PV contributing to a grid-mediated "virtual ZPH". However, in most other North American jurisdictions such FIT programs do not exist.

[6] Indeed, Leadbetter & Swan [27] demonstrated that meaningful peak reductions could be achieved with battery storage alone, though systems would have to be sized larger than those used in combination with other strategies. They suggested a battery-only system should be sized at 3.2 kW/8 kWh in Ontario.

that the most effective measures for reducing peak load also reduced annual electrical energy use by 14%, although annual natural gas use was increased by 13%.

5. Conclusions

Our results are clear: a combination of practical operational modifications (AC cycling, doing laundry later in the evening) and commercially-available technology (exterior shading, modest PV array, energy-efficient lighting) was able to dramatically reduce (in some cases to zero) the peak electrical demand from the grid of a conventional detached house on the hottest days of the year. This particular combination of measures might be unappealing to some householders, due to inconvenience or cost. Nevertheless, more attractive combinations may still reduce peak load substantially. Therefore, utilities and governments facing summer peak supply problems might want to consider (greater) incentives for these measures for retrofit, and policies to encourage the incorporation of such measures in new houses.

Acknowledgements

This work was funded by the Program of Energy Research and Development (PERD) administered by Natural Resources Canada (NRCan), and by the National Research Council Canada. The authors are grateful to Mike Swinton (NRC) for his helpful guidance on the research.

References

[1] A. Porter, Britain facing blackouts for first time since 1970s, Daily Telegraph, August 31st, 2009
URL: http://www.telegraph.co.uk/finance/newsbysector/energy/6118113/Britain-facing-blackouts-for-first-time-since-1970s.html (last access: 2011-03-29)

[2] I.H. Rowlands, Demand Response in Ontario: Exploring the Issues, Prepared for the Independent Electricity System Operator (IESO), 2008.
URL: http://www.ieso.ca/imoweb/pubs/marketreports/omo/2009/demand_response.pdf (last access: 2011-03-29)

[3] M.A. Piette, D.S. Watson, N. Motegi, N. Bourassa. 2005, Findings from the 2004 Fully Automated Demand Response Tests in Large Facilities, Lawrence Berkeley National Laboratory/Demand Response Research Center, Report Number LBNL-58178, 2005.
URL: http://drrc.lbl.gov/pubs/58178.pdf (last access: 2011-03-29)

[4] G.R. Newsham, B.G. Bowker, The effect of utility time-varying pricing and load control strategies on residential summer peak electricity use: a review, Energy Policy, 38 (2010), 3289-3296.

[5] Y. Strengers, Air-conditioning Australian households: the impact of dynamic peak pricing, Energy Policy, 38 (2010), 7312-7322.

[6] G.R. Newsham, B.J. Birt, I.H. Rowlands, A Comparison of Four Methods to Evaluate the Effect of a Utility Residential Air-conditioner Load Control Program on Peak Electricity Use, Energy Policy, 39 (2011), 6376-6389.

[7] C. Buntine, M. Schiler, M. Milne, Zero peak residential electric demand: an evaluation of strategies for eliminating peak residential electric demand in California climate zone 10, Proceedings of the American Solar Energy Society conference (Cleveland, USA), 2007, 770-776.

[8] J. Christian, Zero energy peak from zero energy homes, Proceedings of ACEEE Summer Study on Energy Efficiency in Buildings (Pacific Grove, USA), 2008, 1.37-1.48.

[9] R. Kerr, Zero peak homes: real homes, real savings, Home Energy Magazine, Climate Solutions Special Issue (2008), 34-39.

[10] R. Hammon, Zero peak homes: a sustainable step, Proceedings of ACEEE Summer Study on Energy Efficiency in Buildings (Pacific Grove, USA), 2010, 2.115-2.126.

[11] A.J. Pietila, Reducing the Magnitude and Reshaping the Temporal Distribution of Residential Electrical Loads Purposed to Achieve a Zero Peak House in a Southern Ontario Climate, Thesis for Master of Applied Science in Mechanical Engineering, Department of Mechanical and Aerospace Engineering, Carleton University, 2011.

[12] A. Pietila, I. Beausoleil-Morrison, G.R. Newsham, Zero Peak Housing: exploring the possibility of eliminating electrical draws from houses during periods of high demand on the electrical grid, Building and Environment, 58 (2012), 103-113.

[13] D.S. Parker, Very low energy homes in the United States: perspectives on performance, Energy and Buildings, 41 (2009), 512-520.

[14] CCHT, Canadian Centre for Housing Technology, 2010.
URL: http://www.ccht-cctr.gc.ca/eng/index.html (last access: 2011-08-05)

[15] NRCan, About R-2000, Natural Resources Canada, 2010.
URL: http://oee.nrcan.gc.ca/residential/personal/new-homes/r-2000/about-r-2000.cfm?attr=4 (last access 2011-08-09)

[16] Hydro Ottawa, 2012. URL: https://www.hydroottawa.com/residential/saveonenergy/programs-and-incentives/peaksaver/ (last access 2012-03-23)

[17] J. Gusdorf, M.C. Swinton, C. Simpson, E. Entchev, S. Hayden, B. Castellan, Final Report on the Project to Measure the Effects of ECM Furnace Motors on Gas Use at the CCHT Research Facility, CCHT Report NRCC-38500, 2003. URL: http://www.ccht-cctr.gc.ca/eng/projects/ecm.html (last access: 2012-03-23)

[18] R. Hendron, C. Engebrecht, Building America House Simulation Protocols. National Renewable Energy Laboratory, 2010. URL: http://www.nrel.gov/docs/fy11osti/49246.pdf (last access: 2012-03-23)

[19] SRoeCo Solar, Most Efficient Solar Panels, 2012. URL: http://sroeco.com/solar/most-efficient-solar-panels (last access: 2012-03-23)

[20] M. Santamouris, A. Sfakianaki, K. Pavlou, On the efficacy of night ventilation techniques applied to residential buildings, Energy and Buildings, 42 (2009), 1309-1313.

[21] ASHRAE, ANSI/ASHRAE Standard 55 Thermal Environmental Conditions for Human Occupancy, American Society of Heating, Refrigerating and Air-conditioning Engineers, Atlanta USA, 1992.

[22] ASHRAE, ANSI/ASHRAE Standard 55 Thermal Environmental Conditions for Human Occupancy, American Society of Heating, Refrigerating and Air-conditioning Engineers, Atlanta USA, 2010.

[23] P.O. Fanger, Thermal Comfort, Danish Technical Press, Copenhagen, 1970.

[24] A. Laouadi, A.D. Galasiu, M.C. Swinton, M.M. Armstrong, F. Szadkowski, Field performance of exterior solar shadings for residential windows: summer results. Proceedings of 12th Canadian Conference on Building Science and Technology (Montréal), 2009, 197-210. URL: http://www.ccht-cctr.gc.ca/eng/projects/solar_shadings.html (last access: 2012-03-23)

[25] W. Kempton, C. Reynolds, M. Fels, Utility control of residential cooling: resident-perceived effects and potential program improvements, Energy and Buildings, 18 (1992), 201-219.

[26] J. Gusdorf, M. Armstrong, F. Szadkowski, J. Sager, Summer Shading Performance of Awnings at the Canadian Centre for Housing Technology. CCHT Client Report B-6041.1, 2011. URL: http://www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/b6041.1.pdf (last access: 2012-03-24)

[27] J. Leadbetter, L. Swan, Battery storage system for residential electricity peak demand shaving, Energy and Buildings, 55 (2012), 685-692.

[28] EERE, Incentives and Rebates for Energy-Efficient Windows offered through utility and state programs, 2011. URL: http://www1.eere.energy.gov/buildings/windowsvolumepurchase/pdfs/2011_utility_incentives_for_windows.pdf (last access: 2012-03-23)