Zero Energy Peak from Zero Energy Homes

Jeff Christian, Oak Ridge National Laboratory

ABSTRACT

As the Tennessee Valley Authority (TVA) dealt with record afternoon electricity demand during the August 2007 heat wave, a near zero energy home in Lenoir City, TN was actually selling power back into the system.

Utilities pay premium prices during peak demand periods to supply power to businesses and homes. Instead of contributing to the load, the Near-Zero-Energy homes, in one development in East TN during the 113 year record hot August contributed to the grid.

These homes combined energy-efficient technologies with rooftop solar collectors and 11 kWh of battery storage and energy management controls--to become a potential utility peak power supplier.

The affordable ZEH concept has been under design and evolution in five side-by-side Near-Zero Energy Homes, since March 2002. The concept is working, as evidenced in Augusts' brutal heat, which at times reached 100 ^{o}F. This paper shows how these homes can be configured and operated to supply net power during critical peaks like on August 16, 2007 between 5:00 and 7:00 PM Eastern Daylight Saving when TVA hit their all-time system peak. s time,. A well integrated whole house package of technologies used in these homes was able to supply 3kW to the grid during summer critical peak periods.

Increasingly utilities and developers, envision entire neighborhoods of homes that have the ability to be peak power suppliers—with meters that sometimes run backward as the homes generate more energy than they consume. Aggregating about 170,000 of these homes across the Southeast U.S. would produce an equivalent of 1200 MW of dispatchable peak power.

Introduction

Since 2002 the DOE Building America Project collaborated with ORNL, the Tennessee Valley Authority (TVA), and the Habitat for Humanity Loudon County Affiliate, to build five near zero energy homes. (Christian, February 2008)

In August 2007, the hottest in 113 years of recorded history, one of the homes was equipped with the capability to store electricity in batteries for return to the electrical grid at times in which TVA was experiencing electric system critical peaks.

Space conditioning of the unoccupied 2,600 ft^2 house that was built in 2005 (designated "ZEH5") underwent 2 years of detailed thermal performance monitoring from January 1, 2006 until December 31, 2007. The first four homes are all occupied and have one year of performance measurements. The best-performing occupied home during the 2006 calendar year was the 1,200 ft^2 two-story home, "ZEH4," which experienced average net energy costs of less than $0.50/day. This is compared to average energy costs of $5 to $6 for homes in the same region.

Data collected in the test homes provide a continuous record of the demand for electricity under real-world conditions as demand peaks and ebbs during the course of a day. It happened that during part of the test period (the summer of 2007), East Tennessee was experiencing record high temperatures and drought. TVA reached its all-time record at around 6 p.m. EDT (eastern daylight savings time) on August 16, by meeting a demand of 33,482 MW. Also, because of the extreme drought conditions, hydropower, TVA's cheapest source of electricity, had been cut by 40%, transmission line capacity was at its lowest rate, and cooling water for generation plants was limited.

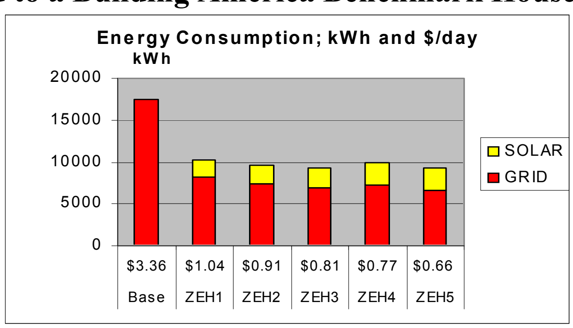
ZEH5 maintained comfortable temperature and humidity during the hottest part of the day while demanding no energy from the grid. There were TVA critical system peak times between 5:00 and 7:00 PM, during August when electricity produced by the homes was flowing back onto the grid. The research has shown that the all electric ZEHs use about 40% less electricity, on an annual basis, when compared with non-ZEH of similar size and occupancy if the ZEHs are outfitted with energy efficiency features and photovoltaics alone. Adding features, such as solar water heaters, "demand-side" tools, such as "smart" controls (which govern energy use and storage) and batteries, contribute to even greater savings.

The results show that "precooling" a ZEH (lowering the thermostat 2 ^{o}F for a few hours before the system peak and setting up the thermostat during the critical peak 3 ^{o}F) saves substantial peak energy with no impact on thermal comfort. This work shows that a summer peak load reduction from conventional homes to ZEHs can save on average 7 kW/home. Linking 170,000 of these homes together by dispatchable controls would build a 1200 MW green power peaking facility, close to TVA's goal of 1,400 MW by 2013 from demand side management.

Background

The five houses, designated ZEH 1-5, have very low energy costs as shown in Figure 1. Daily average costs range from about \$1.00/day to \$0.66/day. These performances are all based on at least 3 occupants. ZEH4 was constructed in 2005 and is shown in Figure 2.

Figure 1. Daily Total Energy Consumption of the Five Near Zero Energy Houses Compared to a Building America Benchmark House for ZEH5



Source: Hendron ,2007

Figure 2. ZEH4, 1200 ft^2 with 2 Ton 17 SEER Air-Source Heat Pump

Scope

Demand responsive ZEH. ZEH5 is a 2,600 ft^2 near zero energy home. A two ton Waterfurnace geothermal heat pump provided the space heating and cooling. The measurement period ran from January to December 2007. The measured data were used to validate a whole house simulation model, which in turn was used to generate a predicted performance with occupancy for comparison with a benchmark house with similar occupancy (Christian, February 2007). In July 2007, a Gridpoint energy management system (Gridpoint 2007) was installed in this house to demonstrate the peak load reduction potential of the combination of energy efficiency, 40 ft2 flat plate closed loop-solar water heating, 2.2 kWpeak grid-tie- on-site solar PV(the PV performance data was taken simultaneously from the system on ZEH4 which had the same orientation and slope as that of ZEH5), battery storage and smart demand side management (DSM), during electric utility critical peak periods.

ZEH5 was designed to attain near zero peak energy and near zero annual energy-home for use in the mixed humid climate. Use of thermal mass and simple Demand Side Management/ Energy Management System (DMS/EMS) (such as pre-cooling strategies) were emphasized in the design. The house meets U.S. IRS requirements for the $2000 builder business tax credit. .

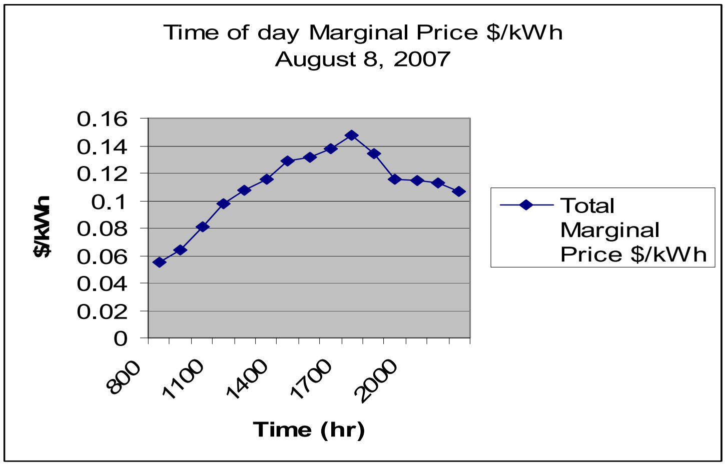
Summer of 2007 Heat Wave

The day time occupants in ZEH5 set the thermostat at 73 F. It had been kept fixed at that temperature 24/7 for the entire cooling season up to mid August. All of these test houses are continuously maintained to comply with the ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy (ASHRAE 1995).

On August 9, 2007 *TVA Today*, an internal news letter reported; "*TVA met its latest record power demand Aug. 8, of 33,344 megawatts at 6 p.m. EDT when the average temperature across the Tennessee Valley was 98 degrees Fahrenheit.*"

PJM* provided 'estimated' real time prices for 08/08/2007 at the TVA/PJM interface, in $/kWh. Figure 3 indicates peak prices at 17:00 (6:00 PM EDT).

Figure 3. Real Marginal Costs during One of TVA's Peak Days*



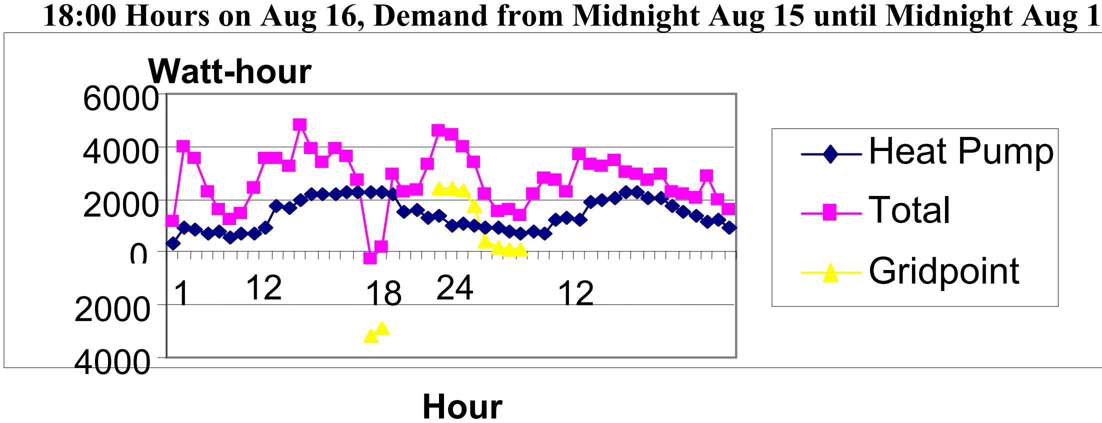
*PJM Interconnection is a regional transmission organization (RTO) that coordinates the movement of wholesale electricity. PJM is a federally regulated RTO that acts independently and impartially in managing the wholesale electricity market. PJM provides real-time electricity prices. PJM's wholesale electricity market establishes a real time market price for electricity by matching supply with demand. http://pjm.com/about/overview.html

The TVA summer peak each day was at 6 pm EDT or 17:00 Central Daylight Time. Table 1 shows that the power TVA had to purchase to meet peak demand cost $0.148/kWh. At the time TVA residential rates were a flat 24/7 $0.07/kWh. TVA has a fuel escalation cost factor in their rate base, which allows them to recover this added cost the next quarter, in this case October through December 2007.

On August 16, 2007 TVA announced that" historic drought conditions across the Tennessee Valley in 2007 have cut TVA's least expensive generation resource, hydropower, by more than 40 percent. The period of January 2007 through July 2007 is among the driest on the 113 year record.

According to Brooks Clark, TVA Communications, the eventual TVA all time system peak was hit on August 16 with 33,482 MW at around 6:00 PM EDT. The ZEH5 Gridpoint platform was programmed to dispatch 3.3 kWh for one hour before the absolute peak and one hour after. The results shown in Figure 4 are that the net load from 5:00 to 7:00 PM, are zero.

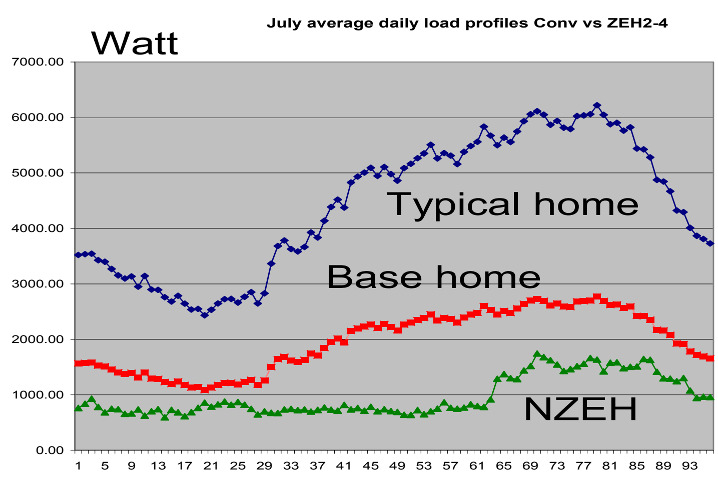
Figure 4. ZEH5 Energy Demand during TVA's Record System Peak of 33,482 MW at 18:00 Hours on Aug 16, Demand from Midnight Aug 15 until Midnight Aug 17



ZEH Peak Load Potential

The energy efficiency features and the solar PV system reduce summer peaks by 40%. Without any demand side management features like controls, battery storage, and precooling these near zero energy homes have been found to save 1.5 kW or about 40% compared to the same size house with identical occupancy usage patterns (Christian 2007). About half of this savings comes from the energy efficiency and the other half from the PV. Figure 5 shows an average daily peak load reduction for July during the 2004-2006 Lenoir City, TN test house at 15-minute intervals. The average difference between the ZEH2-4 and the baseline home is 1.1 kW. These data are from the test ZEHs which do not have solar water heaters. On hot sunny days when critical peak periods occur the solar charge should contribute to an even lower ZEH peak. Across the entire TVA service area, distributor hourly load data indicated the average residential summer peak load in July and August 2006 was 4.34 kW per household. There were 3,726,056 residential customers which equates to a peak residential demand of just over 16,000 MW. Thus, the residential sector accounts for approximately half of TVA's system summer peak. Approximately 32% of residential customers have non-electric water heating. Some of these homes also have gas appliances, like dryers and cooking stoves which make 4.34 kW conservatively low when comparing all electric homes as is the case in Figure 5. The top line in Figure 5 is hard data from an all electric 4000 ft^2 house with a Seasonal energy efficiency rating (SEER) 13 Heat Pump and a, no longer commercially available, Enviromaster International 50 gallon Heat Pump Water Heater. This shows an average peak of 6 kW over a 30 day period in July.

Figure 5. NZEH July Average Peak Load Savings, 72 (15 Minute Interval of the Day) Represents the 6:00 PM Critical Peak, Typical Is a 4000 ft2 All Electric House in Same Climate with SEER 13 AC and a Heat Pump Water Heater.



With demand side management which includes a dispatchable on-site battery bank another 3 kW critical peak reduction available. In August 2007 TVA and LCUB (Lenoir City Utilities Board, a TVA distributor) residential base rate was a flat $0.07/kWh. The TVA 2007 Strategic Plan calls for time-of-use rates. A DSM pilot project was running in 2007 with TVA distributor Electric Power Board (EPB) in Chattanooga, TN. The information gathered from this pilot is used to generate a best guess 'synthetic rate design' to conduct economic analysis for peak load savings, for example by dispatching battery storage and increases in off peak usage to recharge the battery bank. A Gridpoint energy storage and control unit < http://www.gridpoint.com/consumer/products/connect/> was installed in ZEH5, a Habitat for Humanity test house in Lenoir City, TN on June 28, 2007. The prices and scheduling information for the TVA / EPB time-of-use pilot had three levels:

1. Off-Peak rate is $0.044
2. On-Peak rate is $0.124 1400 to 2000, June-Sept.; 600 to 900, Dec - Mar; and 1700 to 2000, Dec- Mar.
3. Critical-Peak rate is $0.251 limited to 90 hrs /year, no more than 6 hours per instance

Ralph Boroughs, TVA Project Manager, recognized that large numbers of Gridpoint-like systems installed, and operated with only these price signals, could be disadvantageous to TVA. The concern is that this rate structure would create new peaks where the current "shoulders" are now. This insight lead to a fourth control state for the "'shoulder" hours, where the GridPoint unit would neither charge nor discharge. (If there were a shoulder price, it would probably not motivate either charge or discharge, since there would be more to gain by waiting.) Effectively, this would limit the recharge load to between 2200 and 600 CPT, summer and winter.

With this background a "synthetic" rate design was developed by the TVA, Gridpoint, and ORNL team. This synthetic rate structure was generated specifically to assess the cash flow potential reflecting the situation in the summer of 2007.

All times are Eastern Daylight Time (Eastern Standard Time, with Daylight Saving observed) since that is were the test houses are located. The weekends include Saturday and Sunday and are always off-peak rates.

The schedule for the entire year is broken up into five periods as shown in Table 1: off-peak, on-peak, and critical peak rates remain the same as above. The most likely critical peak periods will be driven by weather not by only time but it is interesting that 9 of the 10 all time peaks in August 07 were within the two hour period from 1700 to 1900 EDT, the one that was not ended up occurring at 1600 on August 24, 2007.

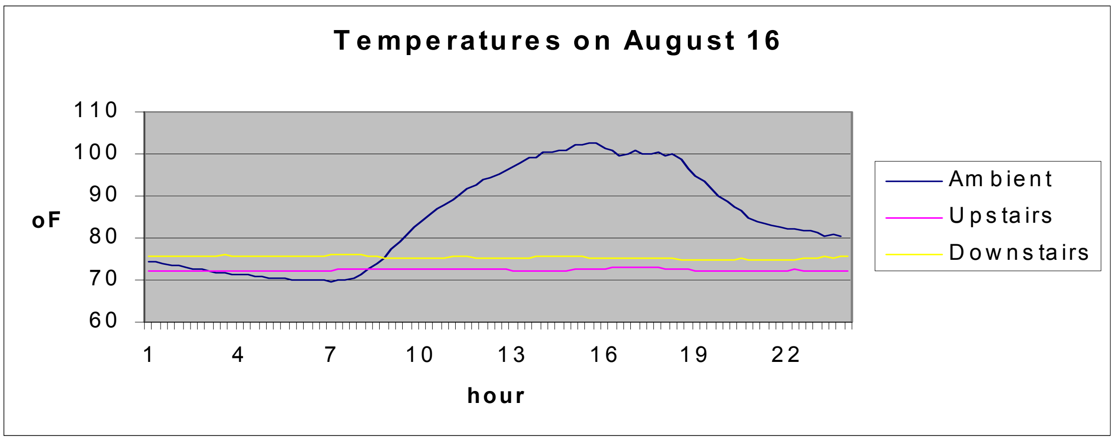
Table 1. Proposed Synthetic Rate Periods

Winter	Spring	Summer	Summer Critical	Fall
Dec - Mar	**Apr - May**	**June & Sept**	**July – Aug**	**Oct - Nov**
Off-Peak 0 – 700 On-Peak 700 – 1100 Off-Peak1100 – 1800 On-Peak 1800 – 2100 Off-Peak 2100 – 2400	Off-Peak 0 – 2400	Off-Peak 0– 1500 On-Peak 1500 – 2100 Off-Peak 2100 – 2400	Off-Peak 0 – 1500 On-Peak 1500 – 1700 Critical Peak 1700 - 1900 On-Peak 1900 – 2100 Off-Peak 2100 – 2400	Off-Peak 0 – 2400

In Figure 4 the energy loads for ZEH5 are shown for the TVA system current-record peak day, (August 16, 2007; 34,482 MW at 6:00 PMEDT). ZEH5 energy efficiency features and the Gridpoint reduced ZEH5 (2600 ft^2), to zero demand for the entire two hour period spanning the TVA system peak at 6 PM. Figure 6 shows the outside temperature rose above 100^{o}F from

1:30 to 6:30 PM. Even at those outdoor temperatures, the bottom two curves in Figure 6 show the interior temperature was maintained at 73°F on the top floor where the thermostat is located and 76°F downstairs. ZEH5 is maintained at a lower than recommended temperature to accommodate the occupants. This house during the measurement period was being used as the Habitat for Humanity Loudon County Affiliate office. This means that no evening meal, cleaning and typical residential energy services were needed. However on average the total annual electric load for the copy machines, office equipment and refrigerator in this house exceeds the average internal electric loads of other occupied houses by 11% in the same neighborhood, and the Building America Benchmark Definition used to compare the energy savings of these prototype houses. (Hendron, 2007) (Christian, April 2008)

Figure 6. Temperatures on the Day TVA Hit an All Time Peak System Load, August 16, 2007

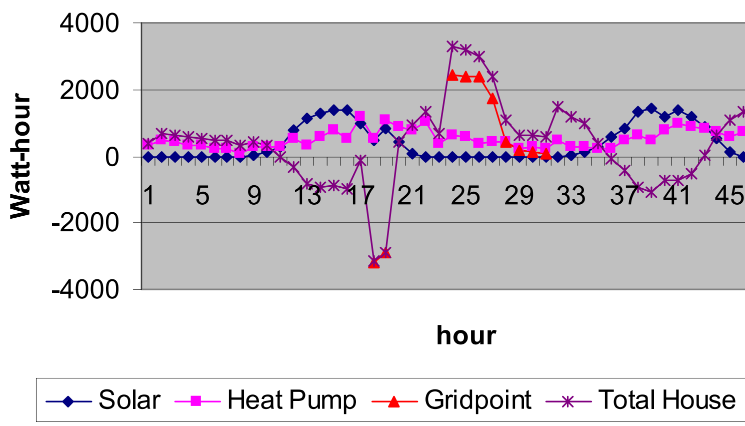


If, on this same day the same Gridpoint equipment had been installed in the three-occupant ZEH4, a 1200 ft^2 house right across the street with the same orientation and combination of energy efficiency and 2.2 kWpeak of PV, ZEH4 actually would have supplied the grid a net 3 kWh as shown in Figure 7. An estimated total house energy demand is shown for two days starting at 1:00 AM on August 16. The solar PV during the critical peak from 17:00 to 19:00 would still be generating and the Gridpoint could have dispatched about 3.3 kWh for the two hour record peak period on August 16. Figure 8 is the same type of display but for August 8 and on this particular day more energy consuming activity during the critical peak period was occurring, which would result in a total house load of zero. Figure 8 shows the whole house measured hourly energy demand and what it would have looked like if the Gridpoint equipment was installed in this occupied house equipped with 2.2peak kW solar PV system installed on the roof.

Dispatched power and recharge energy for the all time TVA system peak on August 16 is also indicated in Figure 7. Actual recharge in ZEH5 was programmed for an eight hour period starting from 23:00 on August 16 and takes about 4 hours. The full recharge consumed 9.74 kWh and the actual dispatch during the 2-hour critical peak period was 6.1 kWh. This represents single-day efficiency for the Gridpoint of 62%. For every 1 kWh of battery power dispatched it took 1.6 kWh to recharge.

Figure 7 also shows the 2 ton air source heat pump was running throughout the entire period. The peak demand from this unit is about 1.6 kW. ZEH4 is a TVA green power generation partner, so we can examine some potential cash flows if the Gridpoint and the synthetic power rates would have been in place. The added savings from the Gridpoint dispatch would be $0.15/kWh X 6 kWh or $0.90 plus the $0.25/kWh X 6 kWh or $1.50 by dispatching during critical peak. This totals a daily savings of $2.40. The recharge cost is 9.47 kWh X $0.044 or $0.42. Thus for the day the unit made $1.98. If each summer all 90 hours of critical peak are exercised this totals $89.10 savings per year. To conduct a life cycle cost analysis the first cost of the batteries and the battery life is needed.

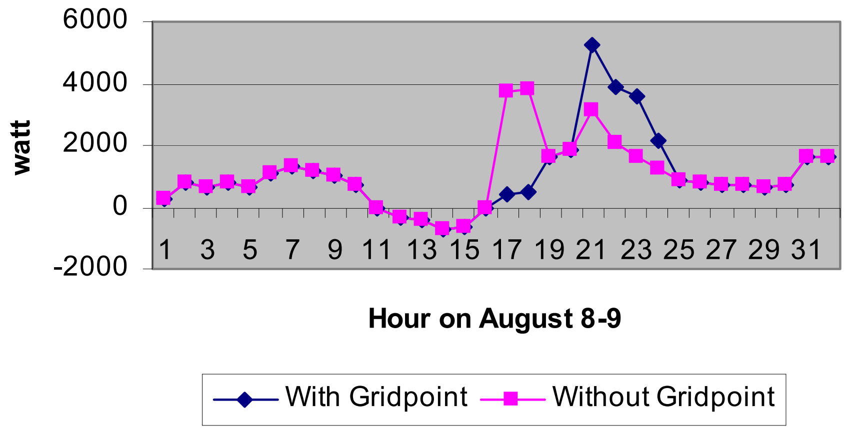
Figure 7. Occupied ZEH4 with Assumed Gridpoint on TVA Peak Day and Part of the Next Day to See the Full Recharge Energy Needs of the Batteries. The Figure Shows Hourly Demand from Midnight August 15 until Midnight August 17.



Since August 14, 2007 the authors dispatched, through internet commands, 9 times and recharged for an 8 hour period each night after a dispatch event for ZEH5. The average measured dispatch was 6.15 kWh. The 8 hr charge that evening and next morning on average used 10.38 kWh. That is an average efficiency of 60%. We did a separate trickle charge on three occasions that totaled 5.9 kWh. For the entire period from August 14 until September 17, 2007 we dispatched 55.4 kWh and recharged the batteries with 99.35 kWh. The efficiency over this, about one month, period was 55% (the typical round trip efficiency of pumped storage is around 78% according to Ralph Boroughs, TVA). If all these dispatches were on the “critical peak” that would have made 6.15 kWh X $0.251/kWh = $1.54, the recharge off peak cost 10.38 kWh X $0.044/kWh = $0.46. This converts to a savings of $1.08/day. If 45 critical 2 hour peak periods per year could be addressed this converts to $48.60. In addition to the recharges after each dispatch event three off-peak trickle charges on weekends were needed, which amounted to 5.9 kWh X $0.044/kWh = $0.26. This results in a positive cash flow of $48.35/year. This is lower than the number from the ZEH4 house above because ZEH5 does not have the PV system on its roof nor the more favorable buyback offer from the utility.

TVA is concerned not only about the critical 1700 to 1900 critical period but as can be seen from the rate schedule in Table 1 also the broader 1500 to 2100 peak. Demand side management systems need to have the capabilities in these near zero energy houses to work with the broader “peak” period. This means dispatching for more hours at lower wattages. If multiple ZEHs were aggregated this could be accomplished by spreading the 2 hour dispatches in each house across the longer six hour peak period. At the time of this testing the equipment and software could only dispatch 3.3 kWh per for either one or two hours.

Figure 8. ZEH4 and Gridpoint on August 9 Took Total House Load to Zero



Note: The X-Axis Units Are Hour from 1 AM on August 8, 2007 through 8:00 AM on August 9.

Pre-Cooling in a ZEH Leads to Additional Peak Savings

On August 24, 2007 the programmable thermostat was set to still meet the occupant preferences but to conduct an examination of the additional critical peak savings attainable by pre-cooling strategies. From August 25 until September 11 the thermostat, which had been set at 73 ^{o}F all summer, was programmed to 71 ^{o}F starting at 1300 until 1700. The results are some extra energy is needed to chill the entire house from 73 ^{o}F to 71^{o}F. The pre-cool start at 1300 meant that the extra energy would be used mostly during two off peak hours since the peak period as shown in Table 1 doesn't begin until 15:00. The set point is then turned up to 76^{o}F from 1700 -1900 coinciding with the battery dispatch and 2 hr critical peak period.

Figure 9 shows the heat pump energy going to near zero as a result of the thermostat setup from 71 ^{o}F to 76 ^{o}F during the 2 hour critical peak period. The geothermal heat pump, circulation pump and fan for mechanical ventilation had been demanding about 2200 watts up until the temperature setup to 76 ^{o}F. The whole house load goes as low as -3000 watt during the critical peak. August 28 had 19 cooling degree days base 65 F (CDD_{65}), almost as many as the record breaking August 16 when TVA hit the all time system peak with 21 (CDD_{65}).

Figure 9. Pre-Cooling Cuts Another 2200 W from the Critical Peak

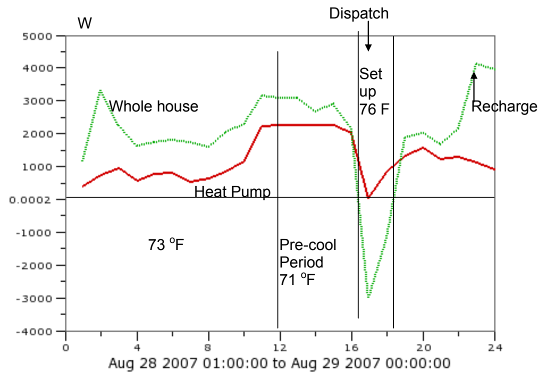
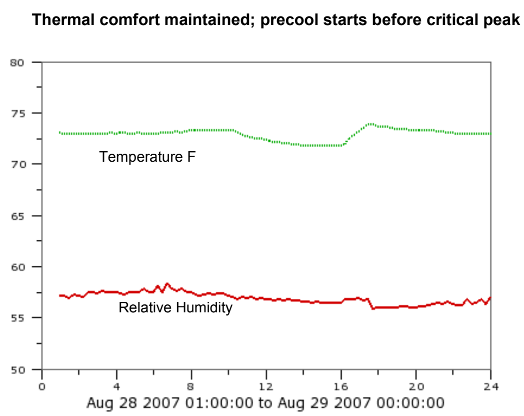


Figure 10 shows the interior temperature and relative humidity during this pre-cooling test day. Inside air temperature rose only to about 74 ^{o}F and the RH is minimally impacted by shutting of the AC for a two hour period after pre-cooling ZEH5 with a ground source heat pump earlier in the day. ASHRAE 55 suggests in the summer that at 74 F the RH needs to be below 70% during sedentary activities.

Figure 10. Thermal Comfort Maintained during Pre-Cool and Thermostat Setup During Critical Peak



Pre-cooling ZEH5 prior to anticipate system critical peak and then raising the thermostat during the critical two hour period does not seem to demand a significant amount of additional energy. Daily geothermal heat pump demand per (CDD_{65}) for 12 days in August with a fixed thermostat temperature of 73 ^{o}F compared to the same metric for 12 other days with the pre-cooling strategy describe above increased energy demand by less than 2%. This very modest impact is believed to by attributable to the well insulated, airtight envelope with extensive basement thermal mass located inside the insulation layer.

Conclusions

Table 2 itemizes the major components of peak-power savings for a fully-equipped ZEH. Total peak load savings potential in houses like ZEH5 range from 5.5-11 kW, depending on the type of house used for comparison. Table 2 provides the break out of how each of the major components in a fully equipped ZEH contributes to this peak load savings. Based on the measured data collected from this project with testing over the hottest and driest summer in 113 years a low, average and high estimate of the per house peak load savings is presented. This is with the focus of a critical peak period of 2 hours from 1700 to 1900 on hot summer days. The high estimate is based on the average total load for a typical all electric TVA residence summer critical peak, which around 6 kW (Figure 7). During this testing period TVA hit 10 of their all time high system peaks.

Table 2. Summary of Peak Load Savings from Near Zero Annual Energy Homes in East Tennessee

Component	Low estimate of Peak load savings kW	Average Peak load savings kW	High estimate of Peak load savings kW
ZEH Energy efficiency	0.55	0.75	4
2.2 kWhp Solar PV	0.55	0.75	1
Battery dispatch	2.9	3	3.1
Pre-cooling strategy	1.5	2.5	3
TOTAL	5.5	7.0	11.1

1200 MW TVA ZEN (Zero Energy Neighborhood) Peaking Plant

The final conclusion resulting from this study is that these all electric houses if equipped like ZEH5 and ZEH4 have the potential of reducing net demand from 4.0 kW/resident could be reduce to -3kW or a net peak load shed of 7.0 kW per residence. That means that if 170,000 in the TVA service area could achieve the performance level of ZEH4 and ZEH5, it would effectively equal a dispatchable green power plant generating 1200 MW. That is equivalent to TVA's DSM strategic goal. Historically the TVA service territory has been adding about 60,000 homes per year.

References

ASHRAE, 1995, "Thermal Environmental Conditions for Human occupancy", ANSI/ASHRAE Standard 55a, 1995.

Christian, Jeff and Bonar, Jacob, "Building a 40% Energy Saving House in the Mixed-Humid Climate", ORNL/TM-10081/08, Oak Ridge National Laboratory, February, 2008

Christian, Jeff, ORNL "Zero Peak Communities Electric Utility Benefits", ASHRAE Envelopes X Conference, Clearwater Beach, Fl, December 2007.

Christian, Jeff "2600 ft2 Home that has 50% Energy Savings in the Mixed-Humid Climate; ZEH5 2-Story ORNL DRAFT report, April 2008

Gridpoint 2007, http://www.gridpoint.com/smartgrid/overview

Hendron, Robert. 2007. "Building America Research Benchmark Definition, Updated December 15, 2006," [Current version.] NREL/TP-550-40968, http://www.eere.energy.gov/buildings/building_america/pdfs/40968.pdf Golden, Colo.: National Renewable Energy Laboratory.

Eldridge, 2007, Eldridge, Maggie, Prindle, Bill, York, Dan, and Nadel, Steve, 'The State Energy Efficiency Scorecard for 2006' http://aceee.org/pubs/e075.pdf?CFID=3212463&CFTOKEN=88715643 ACEEE Report # E075, June 2007

Nadel, 2000, Nadel, Steve, Kubo, Toru, and Geller, Howard, "State Scorecard on Utility Energy Efficiency Programs", http://www.aceee.org/pubs/u004.htm April, 2000

Cabbage, 2007, Cabbage, Bill, "Near-Zero homes beat the heat", ORNL Reporter http://www.ornl.gov/info/reporter/ issue No. 92, September 2007