The Ravina Project

Household Thermodynamics – Summer

Household Cooling in a Warming World

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2013/04/30

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REV 06

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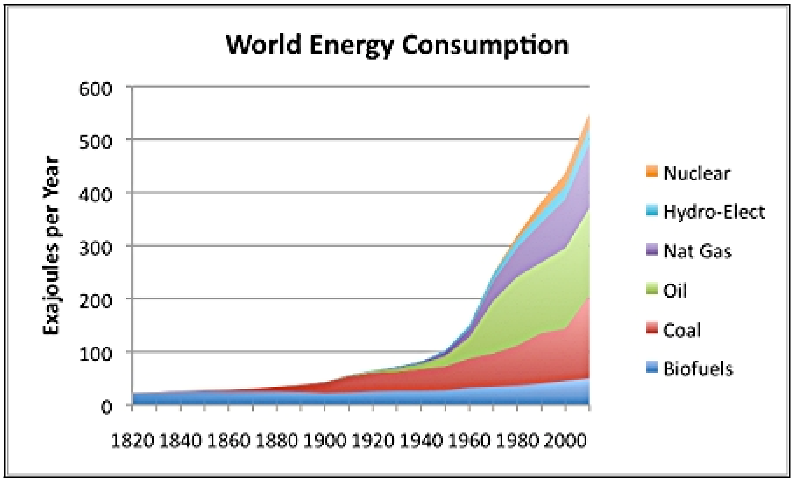
Introduction

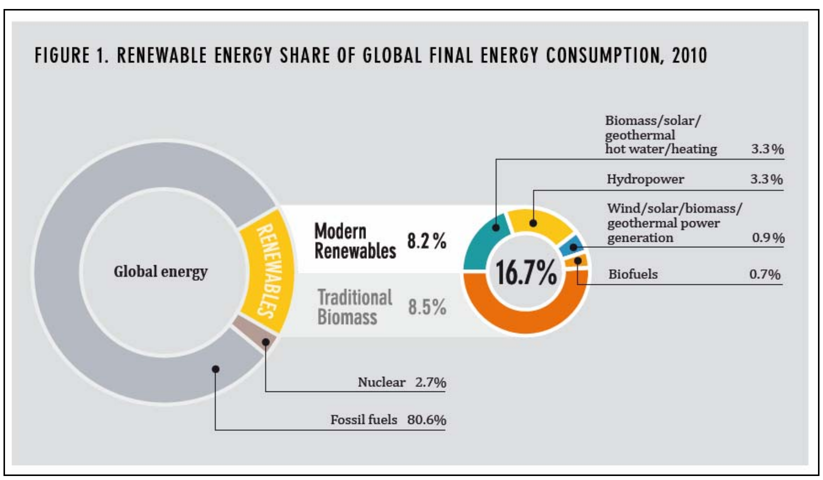
This paper has grown out of our past papers on Household Thermodynamics in which we have calculated our wintertime household heating efficiency. That calculation allowed us to make changes to the house and determine if they made a difference the next winter. We have several similar goals for this paper but first let's set up our argument by looking at a few graphics.

The graphic below gives us an appreciation of the exponential growth in world energy consumption up to 2010 broken out by energy source.



Source: World Energy Consumption by Source, Based on Vaclav Smil estimates from Energy Transitions: History, Requirements and Prospects together with BP Statistical Data for 1965 and subsequent

Look at the fossil carbon component to this graph and imagine what the graphic would look like without the coal, oil and natural gas. If we keep nuclear, biofuels and hydro we are left with 100 Exajoules of energy to run the world at a present energy consumption of five times that much.



Source: REN21 Renewable Energy Policy Network for the 21st Century

The graphic above details the amount of energy that must be replaced with renewables and some form of non-uranium based nuclear energy (Thorium?). It will be a brutal War against CO2.

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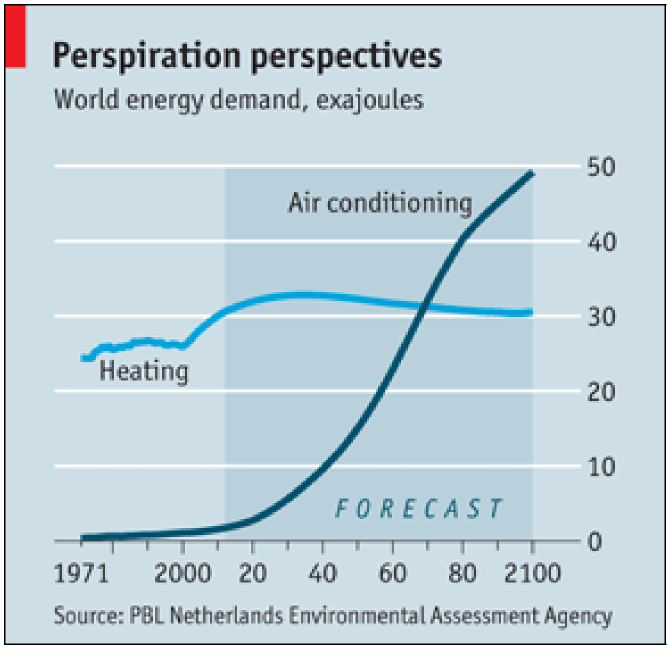

One joule is equal to one Watt-second, that is, the power of one Watt used for one second. One Exajoule is equal to 1.0E+18 joules. Looking at the graphic it seems we used one Exajoule for cooling in 2010 and going forward the yearly increase will be almost exponential.

So how much is one Exajoule in a much more common measure of a kiloWatt-hour?

On joule is equal to 2.78E-7 kWh so 1.0E+18 joules would equal 2.78E+11 kWh or 278,000,000,000 kWh or more conveniently, 278 TWh (Terawatt-hours).

By this graph we will easily double or triple this total energy used for cooling by 2020 and use 50 times more by 2100. Why? It's because we have a huge population moving from the third world into the second world with increased demands for cooling, another group moving from the second world to the first world with huge cooling demands plus another 2 billion people added to the world by about 2050. And if that's not enough, this occurs against a background of global warming on a huge scale during this century.

The issues going forward in the century are many but these stick out as being important:

- Huge increase in energy used for cooling,
- Increase in global average temperature of 2 to 6 degrees C over pre-industrial by 2100,
- Large demand for low energy household cooling techniques,
- Cooling efficiency will become part of a much larger ideology of efficiency management, experiment and implementation … call it a 'do-more-with-less' movement.

Keeping cool will not be optional as we move forward in this warming century, household cooling will be a necessity for a vast portion of our worldwide population/work force.

This has been a rather lengthy introduction to this paper but we want to provide a context for our work. One focus of this paper is upon calculating summertime cooling efficiencies. If it is possible to calculate our household cooling efficiency we have a value which we can refer to year after year. It allows us to experiment with different cooling methods each summer and determine whether those methods are better or worse.

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We have specific goals for this paper:

- **Can we calculate our household cooling efficiency?** Is it possible to calculate household cooling efficiency expressed kiloWatt-hours used per Cooling Degree Day or kWh/CDD? If we are able to calculate our cooling efficiency, can we verify it?
- **What is the household response to heat?** As the days get hotter how much more energy do we use? Do we use gradually more energy to cool the house or is there a temperature point where household energy demands rise dramatically?
- **What is the household response to Humidex?** As the days get more humid how much more energy do we use? Do we use gradually more energy to dehumidify the house or is there a Humidex temperature where household energy demands rise dramatically?

We also want to use this paper to educate the public about the physics of household cooling to the extent that people will evaluate their own households and implement cooling efficiencies.

Note our method of data collection. We use the ‘double-look’ method. We record the meter reading on first look. We look away from the meter and then back again. We take another reading and verify our written value. We find this simple method catches errors especially when we take hurried outside readings during inclement weather. Over the years we’ve taken readings wearing almost everything including snowshoes.

There are other standardized methods that require two observers to agree on a reading. We find it inconvenient for both of us to be out doing the same thing. The above method is our compromise position/method on this issue.

We found that the cooling efficiency calculation is much more difficult especially in the area of data management. The reason of course is that we power our household with electrons. That might not seem like much of a problem until one looks further into it. Electrons power cooling devices as well as all non-cooling devices and since we can’t ‘tag’ electrons as to which does what … cooling or everything else … it becomes complicated.

House vs. Household

It was Jane Jacobs in one of her books who alerted us to the distinction between a house and a household. This distinction is huge when trying to calculate the thermodynamic properties of a house because we are really calculating the thermodynamic properties of a household.

We use the term ‘house’ when we refer to the physical structure of the house and we use the term ‘household’ to include the house and the people, plants and pets living in it. This might not seem like a big deal on first thought, but in fact the data shows that there is a huge difference between them.

Let’s do a ‘thought experiment’ and try to tease out the difference between a house and household from a heat flow perspective.

Suppose we have a ‘test’ house which is sealed up and unoccupied and which contains central air conditioning keeping the internal temperature below or equal to time-of-day preset temperatures programmed into a computer aided thermostat. The heat enters the house through various avenues. As the daily average temperature rises outside, the air conditioning is engaged to modify the internal temperature. We should see a consistency in energy consumption as the outside temperature rises and falls. The house has only one way of shedding heat, that is, employing an air conditioner heat pump, so if we plot the Cooling Degree Days against the seasonal energy usage, our plot would more or less track the heat.

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When we plot our summer time energy usage against the daily temperature we see the response almost chaotic on a day to day basis.

How about our test house’s response to humidity? Well there should be none. Thermostats respond to heat only so they would track only the heat portion of the Humidex reading.

The Physics of household summertime cooling

There are several concepts to keep in mind when looking at your own house and trying to understand the summertime heat flow through it:

- dry air is more dense that humid air,
- cool air is more dense than warm air,
- water vapour by itself moves very slowly through still, dry air
- air can be understood for our purposes as a fluid such that convection currents carry heat and humidity rapidly from one place to another.

Dry air is more dense than wet air

To many people including me this statement is not intuitive. I figured, initially, that the weight of water in the air in the form of water vapour would make the air heavy. We aften speak of the air being ‘close’, or ‘dense’ or ‘heavy’ when it is particularly wet / humid outside.

However, such is not the case. The weight of a standard volume of dry air at standard pressure and temperature is about 29 grams. The weight of the same volume of water vapour at the same pressure and temperature is about 18 grams. So if some of the dry air is replaced by water vapour the overall air weight will decrease. The difference in weight is slight but it is enough to make a parcel of wet air less dense than the volume of dry air surrounding it. Hence the parcel of wet air will rise in a volume of dry air just like a cork will rise in a volume of water.

And conversely, left on its own, a parcel of dry air will settle through a volume of humid air just because it is heavier than the humid air.

Cool air is more dense than warm air

The next step in this argument has to do with the physical ability to take the temperature of a parcel of air. This is a very complicated process … much more so than just placing a thermometer into a parcel of air and taking a reading. We aren’t going to go into the Statistical Mechanics of gases here other than to steal from it the idea that when we measure an air temperature, the reading we get is the average air molecular (energy) temperature in that parcel of air. In other words the temperature of a gas is a statistical reading. It means in that parcel of air there are many molecules that are cooler and hotter than the Mean temperature. Also because air temperature is statistical in nature we can infer that a large quantity, 68.2% or so of the individual temperatures of the air molecules are close to the Mean temperature. But we can also infer that the rest … over 30% have quite different temperatures, either much hotter or much colder than the Mean temperature. This distribution of temperature and density occurs in every parcel of air we measure.

We can feel the effect of the difference in air density just by placing our hand over a hot radiator. The hot air is rising from the surface. Air density difference is the prime mover of air around the house and accounts for virtually all of the natural air movement in the house. In many ways air acts like a fluid. This air movement, called convection, is a major mode of heat and mass transfer in gasses and liquids.

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In any part of the house, over a period of time, the hotter and less dense than average parcels of air, rise and the cooler, more dense than average parcels of air, sink. The action by the air itself is a key concept for those who evaluate their own house and plan for energy efficient summertime cooling.

The interesting thing about air conditioners is that they produce both cooler and dryer air, doubling up on the air's potential density increase.

Water vapour moves slowly through dry still air

Just how fast does water vapour move or diffuse through still dry air at a fixed temperature? It moves very slowly at the rate of under 1 millimeter squared per second. The dry air the diffusion rate at 20 C and one atmosphere is more or less about: 2.3 / 100,000 (0.000023) meters squared per second. To move any distance water vapour must be carried by air movement the chief of which is air movement caused by temperature differences. In the short term, humidity is therefore brought into your house by other forces like air convection discussed above and not by water vapour diffusion through dry air.

In many ways this is a nice state of affairs. If our house is full of dry air, the humid air outside will have a tough time getting through our walls or partially opened windows. In other words humidity can't really 'force' itself into our house in the short term, it must be carried by other forces. Wind blowing through the house or through cracks in the house could be a prime carrier of humidity into the house.

Air as a fluid

We all have experienced sitting in a 'draft' coming from some place. Many times we can trace it down to a fan or air outlet that emits air under pressure into a room. But at times the source of the draft is not apparent … like sitting on the bottom steps of the stairs to the second floor. There is always air moving at that location because that's the only way air can move between the floors. It is a pinch point between the large volumes of air on the first floor and on the second. In the summertime the more dense colder/dryer air travels down the stairs and warmer/wetter less dense air travels up.

So bottom line, when evaluating your house, make sure that air flow is taken into consideration as the prime mover of heat and humidity.

Using Physics to create a comfortable summertime household

We have all the concepts we need to create a comfortable summertime household. We know that cool air is denser than warm air and we know that dry air is denser than wet air so our goal is simply to work out a strategy for keeping our house full of dense air.

With respect to keeping the house drier rather than wetter in the summer time, one more idea is good to know. It takes lots of energy to evaporate water. If you have ever, when cooking, had to reduce a liquid by boiling off the water, this idea comes as no surprise. The same thing happens when our bodies cool themselves by sweating, that is, producing water on the surface of our skin. If we sweat in a room full of moving drier air the water on our skin evaporates faster. Each gram of water, which is one cubic centimeter (cc) in volume, takes about 540 calories of heat energy to be completely turned into water vapour. The heat is withdrawn from our skin and we feel cooler.

Bottom line, in dry air we can be comfortable in much warmer air than we would think which means our house can be hotter and comfortable if it has dry air in it. And further a warmer drier house means we use less energy to cool it on average. Similarly, a cool but humid house is more comfortable than hotter humid house and uses less energy.

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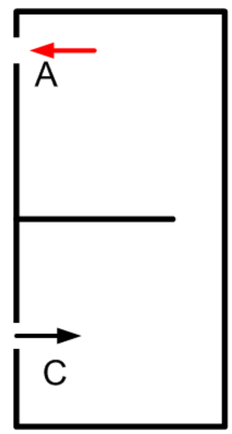
A multi-story house as a chimney

Our analysis of heat flow in the summertime is very different than that done in the wintertime. We want to keep heat and humidity out of our house in the summer time. We want the exact opposite in the winter. Our wintertime insulation keeps summertime heat out but unlike the wintertime, the summertime windows are open for much of the day for weeks at a time in some years. A good description of the household heat dynamic / efficiency is totally different and much more challenging than the wintertime analysis.



Consider a simplified model of a two story house. The house is two boxes attached together with a staircase providing the opening for air movement between floors.

From our understanding of the physics we have discussed above, let's analyze the model and see how it works.

At 'A' we have a fan that exhausts air. It is located at the highest point on the floor. Since it is on the second floor and at the highest point we also know from our physics that the air it exhausts will be less dense than the average air density in the house. In fact we might take the view that the air on the inside of the house at that location is on average the least dense air in the house. We know that this air consists of warm and wet air. So this fan is exhausting air that is probably on average causing us the most discomfort.

Let's assume that the house is sealed up except for an open window on the first floor at 'C'. The exhaust fan places a negative air pressure on the inside of the house so to counteract this pressure, air must flow in from the outside at opening 'C'. As we remember when we were discussing temperature, the temperature of the air is really an average reading of a parcel of air. So bottom line, if the average temperature of the air coming in the window is less than the average temperature of the air expelled by the fan, the house will cool.

But how much will the house cool? That's hard to pin down. The hottest parcels of air coming into the house will rise to be expelled by the fan. The coolest parcels of air will stay around, not rise and probably fall to the floor. These cooler/denser parcels of air will gradually replace less dense air, pushing it upward to be exhausted by the fan. Will the house cool more? Yes it will. As the bottom floor of the house fills with denser air the hotter less dense parcels of air coming in from the outside will be expelled upwards faster because on average the temperature/density of the first floor air is cooler and more dense. Simply put, as this process continues the house becomes even more effective in cooling itself as cooler more dense air hangs around the first floor. The cooling will end when there are not enough cooler parcels of air entering the house to reduce the average temperature. From our experience, this effect is substantial and maintains a cooling effect even on hotter days and even with windows open on the first floor and closed on the second. It is real and powerful. As a former school teacher I taught in old schools which had very high ceilings with long windows. I had a pole that allowed me to open the windows panes right at the top of the windows a good 5 meters above the classroom floor. The windows at the bottom were also opened. We kept the class room cool that way; the hot less dense air migrated upwards to be replaced by outside air coming in below: the chimney effect in action in days before the advent of air conditioning.

Notice we have not mentioned humidity. This process works up until a point when high humidity enters the house. We know from our physics that there is a slight difference in density between humid air and dry air but, and this is important, it is not even close to the density difference between warm and cool air. The 'house as a chimney' does not work on very humid days.

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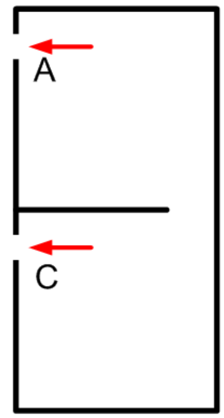
That point being made, on more humid days you feel much more comfortable inside than outside even though the actual amount of water vapour in the air is the same as the outside. In fact the relative humidity inside the house is greater than outside because the air temperature in the house is lower than outside. The air temperature is the key.



The bottom line is that up until a certain point, the discomfort caused by humidity is offset by coolness. We will see that in our data presentation section below in this paper.

Cooling using the chimney effect

Let's now take a look at a diagram of the house that is closer to reality. There are two sets of exhaust fans, one on the first floor in the kitchen and the second on the second floor in the hottest room. These fans are placed at the highest point in the rooms. They exhaust the warmest air in the room and on the floor. The fan at 'C' keeps the kitchen cool.

The kitchen is a hot spot even when cold meals are prepared. The refrigerator dumps the heat it takes from its insides into the room. I can reach behind my fridge to touch a rather hot radiator. It's probably true that the fridge works harder, that is, its radiator is hotter during the summer months. That's probably because the ambient air temperature surrounding the fridge is hotter than in the winter time. As well, other appliances/electronics like the toaster/kitchen TV and the like add to the kitchen heat load presented by other heat sources in the kitchen that have nothing to do with the stove. Therefore the exhaust fan at 'C' is critical because it is in a location which is a constant heat generator for the household during the cooling months. When cooking the kitchen is separated from the rest of the house by a drawn, thick curtain. Heat stays in the kitchen and expelled by the fan at 'C'. Note the open window in the picture. Replacing hot air with cooler external air in the summer time when cooking and a drawn curtain makes for a surprisingly cool kitchen with no heat migration into the rest of the house. Stove top natural gas cooking helps because the heat is instant ON and OFF.

Ground floor cooling issues are basically solved with cooling the kitchen properly.

The curtain is not perfect so some of the hotter and wetter air gets out of the kitchen and travels up the stairwell. It rises to the tops of the rooms and gets picked off by the exhaust fan on that floor at location 'A'.

The second story exhaust fan is placed critically because it cools a room that has a big tube monitor and several computers in it. The picture right looks like it was taken on a hot morning with the sun shield in the closed window.

I'm going to get a flat screen monitor that runs cooler for next summer. The CRT is a great heat source for the office in the wintertime though.

There are other second floor cooling issues.

This is the warmest floor. If the outside air is not too humid there is a good chance that it is as cool or noticeably cooler than the internal temperature on the second floor. We are surrounded

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with large 19 meter tall trees which shade the house from afternoon sun and provide a cooler microclimate via their transpiration.

As we can understand, we need cooler air brought into the house … cooler with respect to the hottest air inside. We know that evaporation cools to the extent of about 540 calories per gram of liquid water. The tree leaves provide this cooling because, odd as it may seem, photosynthesis has a heat limit. The energy harvesting characteristics of the leaves are reduced if the leaves get too hot. Transpiration allows them to stay cool and it allows the house, surrounded by trees, to benefit from this natural microclimate when it is in fan assisted active cooling mode.

Note that Stomata are the pores in the leaves from which water vapour is released to keep the leaf cool. Evidently, as atmospheric CO_2 levels increase, an ancient genetic switch, going back to the Devonian Era, will change the number of Stomata on leaves, which in turn, will allow for less cooling. Our tree shaded microclimate will warm.

Inventory of cooling technologies we employ

Here's an exhaustive list of the technologies we use to keep our house cool in the summertime.

1. **Basement dehumidifier** – This is an 'energy star' appliance built to work efficiently. It is set to a LOW position meaning it reduces the humidity by a small amount. Turning it to a setting where it is ON all the time introduces a large amount of unwanted heat into the basement. So instead of eliminating basement humidity, we just want to control it.
2. **Basement low velocity, high volume oscillating fan** – This fan is on a timer and ON for 12 hours a day to mix up the air in the basement during certain kinds of weather so that humid air pockets do not form.
3. **Basement exhaust fan** – This fan sucks out basement air to be replaced by outside air coming in other windows. It is usually employed when the humidity 'breaks' setting up a situation where the basement is more humid than the outside air. The dehumidifier could be run longer at 400 Watts or the fan could be used at 35 Watts for twice the length of time. The fan wins out.
4. **Exhaust fans in both the kitchen and second floor office** – these double fans are placed at the highest points in both rooms/floors. They expel the least dense air that accumulates near the ceiling.
5. **Window reflectors** – We constructed sun reflectors to be placed in the windows which receive the most morning sun. They are light and are removed when the sun changes its angles upon the house. See the Appendix for more info.
6. **Master bedroom 5000 BTU in-window air conditioner** – This is an Energy Star appliance. It is very efficient in cooling / dehumidifying air and is designed to cool one room.
7. **Master bedroom overhead fan** – This fan moves the air in the master bedroom allowing for better sleep in hotter weather.
8. **Master bedroom input fan** – This is a small 10 inch low velocity (quiet), high volume fan placed in the window to draw in cooler, denser night time air to the bedroom and to flush out hotter bedroom air. Many times it runs all night ensuring good sleeps.
9. **Portable 10,000+ BTU air conditioner on first floor** – This portable (on wheels) air conditioner that is very powerful at both cooling and dehumidifying air.

The object of course in using all these technologies is to provide us with a layered approach to cooling the house. As it gets warmer we employ more technology (energy) until we have to employ air conditioning. We will see the results of this below in the **energy use vs. heat** graphs we have created using our summertime data.

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The five categories of summertime days

To better understand how we put it all together to make for comfortable summer time living without air conditioning except for exceptional circumstances, we divide heating days up into five categories.

No active cooling (1)

The days which require no active cooling typically reach into the low 20s C and have cool evenings. Humidity is not a factor. The overhead ceiling fan in the master bedroom may be turned on LOW. It helps stir up the air. All windows in the house are open including the basement windows. Sun shields may be used in the morning on windows that need them. Any air movement from the outside moving through the house is leveraged for cooling. If a warm meal is prepared in the kitchen, the curtain is drawn and the exhaust fans are used. When the kitchen cools, the curtain is opened and the fans are turned OFF.

Minimal active cooling (2)

The days which require active cooling typically reach the mid to upper 20s C. The same activities described above prevail except for a few differences. The exhaust fans are left on the LOW setting all day and night, the windows are left open as described above and a low velocity high volume (quiet) fan is placed in the master bedroom window to bring in cool night air. The basement exhaust fan is turned on and runs on LOW setting to replace basement air with cool night time air. The oscillating fan in the basement (on a timer) is turned ON at the LOW setting to stir up the basement (unfinished and one big room) air. The sun shields are placed in windows that need them in the morning. They are left there until the sun angles improve and then are taken down in the early afternoon.

Active cooling (3)

These days are typically days which have outside daytime temperatures in the high 20s to low to mid 30s C. The Humidex is marginally higher than the air temp which means the dew point is low. The exhaust fans are on HIGH settings. The windows are open on the ground floor but closed in the basement and second floor. The sun shields are in place during the morning hours. During these days the house is working full bore as a chimney. Everything we do is focused on expelling heat before it becomes a problem during the daytime. The night time air temperature and wind speed determines how the house is configured for sleeping. On many evenings the night time air is cool and breezy allowing for the house to be opened up with little or no active cooling.

The days that are the hottest in this category and have rising Humidex are not hot enough to configure the house to the next stage of cooling. In fact on many of these hotter days in the category we’ve been doing chores, working in the garden or doing errands. But we also need a cool dry room to have a nap or just cool down for 15 minutes or so. In this case we turn ON the air conditioner in the Master bedroom but close the bedroom door. The AC, in a matter of half an hour, cools the room to its thermostat setting and starts cycling ON and OFF. Power use drops dramatically as the duty cycle approaches 20%, that is the compressor part of the AC is ON for one minute in every five minutes. What this whole process gives us is a cool room to snooze in or just cool off in but it does it very cheaply. The power requirements are extremely small as compared to the benefits so derived and of course, small with respect to cooling the whole house.

The AC is turned OFF later in the day because the evenings in this category are cooler.

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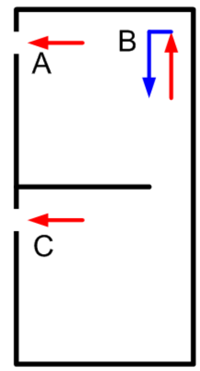
Active Cooling with Air Conditioning (4)

These days are different in really only one respect from the active cooling days described above. The Humidex is high, well into the high 30s. The house is sealed up and the sun screens are used. The exhaust fans are working at maximum setting. The master bedroom air conditioning is ON with the door open and a fan on the floor (the one that was mentioned before in the window at night bringing in cool air) scooting cool dense air out of the bedroom and setting up a convection circuit where the least dense air finds its way into the bedroom to be cycled through the AC. What we try to do is to cool and dry the whole house with a small one room (5000 BTU) AC unit located at 'B'. We do this because the exhaust fans pick off the least dense air and the AC unit both dries and cools the air … it is a huge source of dense air. We also, and this is important, turn the thermostat on the AC to a very low temp setting. We do not want to AC compressor to cycle OFF at any time. The tiny unit cools the whole house … it works at a cooling job way beyond its rating. The curtain to the kitchen is closed when any heat is produced there. Depending on the basement humidity, the dehumidifier, set to a high humidity setting may be ON but cycling the compressor. The basement fan on a timer is ON for 12 hours each day to 'stir up the air'.



For the few nasty evenings as far as Humidex is concerned, the AC unit might run all night but we close the bedroom door (leaving a small space for the cats to get in and out) and raise the thermostat on the AC to a reasonable level. This change allows the compressor to go to its low energy mode cycling on and off every 5 minutes or longer. This AC cycling is the difference between about 500 Watts (compressor ON) and 50 Watts (fan ON).

As soon as the outside situation changes we quickly move to a less energy intensive configuration.

Maximum Active cooling (5)

This situation did not occur during this past summer (2012) but has occurred in the past. It might be the case that during this past summer we avoided this situation because we put in place procedures and house configurations that saved us from going to this stage. Our maximum daily 24 hour cooling energy usage never gets above 30 kWh in all the states listed above. When we hit cooling stage five we have a portable air conditioner which we use. It uses about 1,000 watts, has a cooling capacity of over 10,000 BTUs and a huge dehumidifying capacity. In short, it is a beast!

If the daily energy usage is over 35 kWh then this AC unit has been used for part of the day. Typically we use it to 'get ahead' of a lagging humidity situation in the house. There are times when the window unit upstairs can't cope with the humidity during the hottest part of the day. Running the bigger unit in parallel for several hours solves the problem nicely.

It is interesting to note that we had several days this summer where the Humidex was in excess of 40 C. We were pleased to note that our house was comfortable using the techniques we have developed over the past few years and put into strict practice during the summer of 2012.

Problems with Calculating Summertime Baseline

We have to devise a method which allows us to account for the household summertime energy usage net of any energy used for cooling. We'll call this amount our baseline (non-cooling) energy usage. How many electrons does the house use just to run itself? Included in the house 'running itself' are all the electrically powered amenities we assume will be in operation day and night like

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the fridge. Computers, DSL routers, data switches, WiFi Access Points, TVs, appliances along with powered phones and lighting all consume electrical power.

We figure that the house running without any kind of cooling like our exhaust fans are rare times. And indeed they are. These days usually occur when the outside temperature is optimal both day and night. Every window is open and it remains like that for several days. During these times we argue, we probably are using the baseline amount of electrical energy. This baseline amount should show up in the daily data we gather. We have to be careful though and inspect our data. If we are off-Grid for a period of time, the data gets skewed to the low end because we have no ability to measure how much the house uses independently of the utility and solar charge controller meters. So our data will have to go through a ‘cleaning’ cycle. More on that below.

Daily Baseline Energy Usage Calculation

As we have pointed out above, the calculation of household cooling efficiency is a difficult task. So in order for us to have any chance of getting some kind of verifiable cooling efficiency calculation we have to devise several models of calculating our efficiency. In order to calculate efficiency we must calculate a daily baseline energy usage for the summer season that does not include energy used for heating or cooling. Since we can’t calculate this daily baseline as an exact value, the best we can do is to calculate a range of values in the hopes that we can bracket the correct value on any particular day. In each model that follows we’ll calculate a high and low baseline, the end points of the brackets as it were.

The 2.5th Percentile Method Description

This model which we will call the **2.5th Percentile Method** for baseline calculation going forward in the paper is based upon the following logic and reasoning. We know for certain that the value we want for baseline is located at the very bottom end of the stack of daily energy use values for the summertime if we sorted them smallest to largest. The question is how far up the stack should we go to pick another value in order to have a reasonable likelihood that the ‘real’ or ‘correct’ value for the household’s baseline energy usage on any day is either one of those values or contained between them? It probably is the case that the household’s baseline value is different every day. If we examine the daily kWh usage data for each of the summer cooling seasons we notice there is a lowest daily value and a calculated statistical value at the 2.5th percentile. Briefly, the 2.5th percentile can be calculated using the following method. If we sorted 1000 different datum values from the smallest value to the largest, to select the 2.5th percentile value we would select the datum value located at the 25th place from the bottom of the sorted stack. As you can see both these values are really low in comparison to the rest of the values in the stack. But the value for energy usage that has no cooling component in it is also a very low summertime daily kWh value. For this method we will assume (a huge, but we believe, reasonable assumption) that our range for the baseline will be between the value at the first location on the stack and the value at the 2.5th percentile location end inclusive.

The 18 C Method Description

Our second model called the **18 C Method** for baseline calculation, depends on the daily Mean temperature. In our database we have recorded the Mean 24 hour daily temperature along with all the other daily data we collect. We can therefore single out for each cooling season … indeed from the whole year, all the days whose Mean temperatures fall within a pre-defined range. We can specify the temperature such that it is highly likely that these days require no electrical usage for either heating or cooling. We have chosen the temperature range 18.0 degrees Centigrade plus or minus 2.5 degrees. The range is therefore 15.5 at the low end and 20.5 at the high end. We chose these temperatures because a Mean temperature of 18.0 degrees C is the point at which a day becomes either a Cooling Degree Day or a Heating Degree Day.

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A Mean temperature of 15.5 degrees takes into consideration the overnight temperatures. At this latitude and geographic location, an average of 15.5 C Mean 24 hour temperature ensures that the daytime temperature is close to 18 or more degrees just because the overnight low temperature must be balanced off to end up with 15.5 degrees C as the 24 hour average.

As well, continuing this argument, an overnight temperature low of say 13 degrees C is not furnace or space heater type weather. It is close-up-the-windows-for-the-night weather and let the house heat itself with all the waste heat it produces internally. Similar arguments can be used if the overnight temperature reaches 18 degrees. In that case the windows would be opened.

So what days are candidates for this selection based upon this temperature range? We looked at the data and decided that all days from the start of May until the end of October were candidates even though the heating season starts with June and ends on September 30th. The reason why we opened up the calendar to include other candidates was that we are trying to isolate days which use a minimum amount of electrical energy. We will let our stats package define the Mean energy usage for each season and calculate for us the high and low values for the Mean's 95% Confidence Interval for each season. We will use these high and low values for our baseline bracket values.

The Inspection Method Description

Our third model is called the **Inspection Method** for baseline calculation. We will examine by hand the daily kWh usage for a year and identify a range of days that have low energy usage. We'll take the energy used on those days and use our statistics package to find the Mean amount of energy used and the 95% Confidence Interval around the Mean. We will use the high and low value of that Confidence Interval as the values of our High and Low baseline for daily kWh usage.

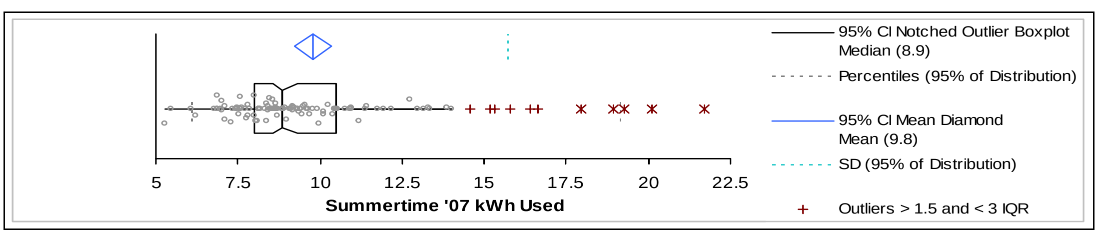
Calculating Daily kWh Usage Baseline using the 2.5th Percentile Method

For this first method we'll show in detail the statistical process involved in the baseline calculation. The other two methods will not be shown in detail but their results will be shown using charts and graphs. We want to ensure that the reader understands we have sufficient statistical number crunching power at our disposal.

Note we use our owned, purchased, commercial statistics package called:
Analyse-it for our statistics work.

What follows are plots of each year's summertime daily kWh data. There's a histogram and another graph which shows the datum value at each of the critical places in the sorted data. The values at the zeroth and 2.5th percentile are calculated by the stats package.

Here's a plot of the 2007 summertime daily kWh usage data:



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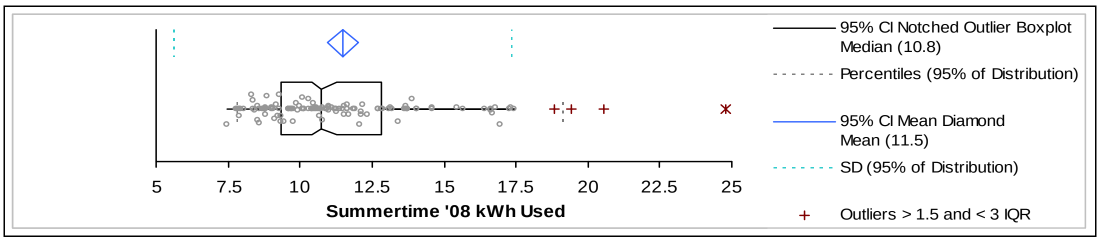
As you can see the bottom end contains just a few daily values. If we look at the percentiles we get the following values:

Percentile		
0th	5.30	(minimum)
2.5th	6.12	
25th	8.00	(1st quartile)
50th	8.87	(median)
75th	10.47	(3rd quartile)
97.5th	19.16	
100th	21.72	(maximum)

So for 2007 we will use the range between 5.30 kWh and 6.12 kWh in which we are optimistic of finding the true daily baseline value for that summer.

The summer of 2008 :



And the percentiles:

Percentile		
0th	7.452	(minimum)
2.5th	7.843	
25th	9.323	(1st quartile)
50th	10.758	(median)
75th	12.826	(3rd quartile)
97.5th	19.179	
100th	24.782	(maximum)

Our daily baseline range for 2008 is between 7.45 and 7.84 kWh.

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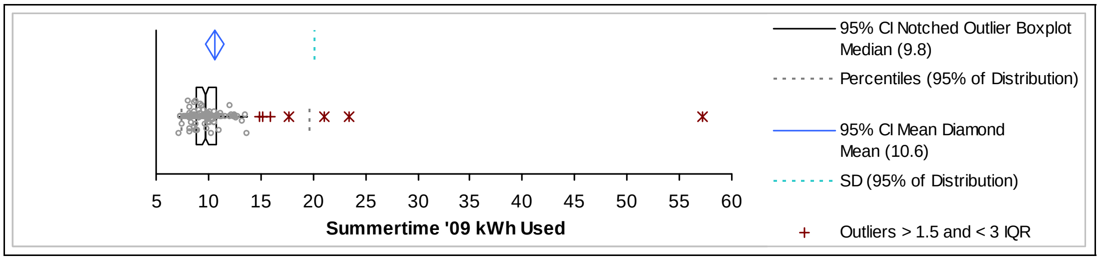
The summer of 2009:



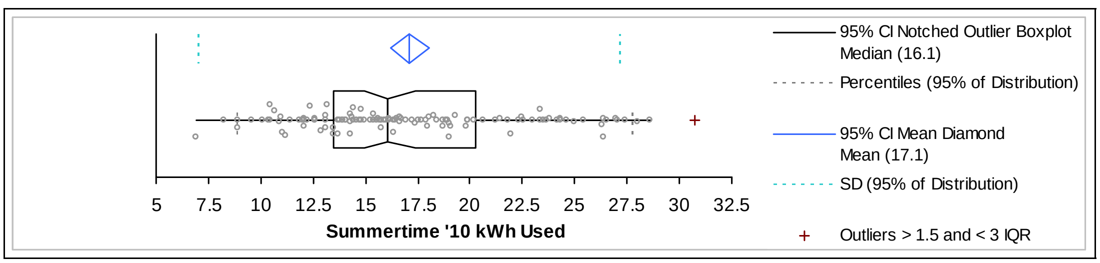
On one particular day it looks like we had everything ON … 57.3 kWh! … Yikes!!

The 2009 percentiles look like this:

Percentile		
0th	7.20	(minimum)
2.5th	7.45	
25th	8.82	(1st quartile)
50th	9.76	(median)
75th	10.79	(3rd quartile)
97.5th	19.71	
100th	57.26	(maximum)

The range of daily baseline values we will use for 2009 is between 7.20 and 7.45 kWh.

The summer of 2010:



And the percentiles are as follows:

Percentile		
0th	6.90	(minimum)
2.5th	8.93	
25th	13.45	(1st quartile)
50th	16.06	(median)
75th	20.23	(3rd quartile)
97.5th	27.76	
100th	30.77	(maximum)

The range of daily baseline values we will use for 2010 is between 6.90 and 8.93 kWh. This range is huge.

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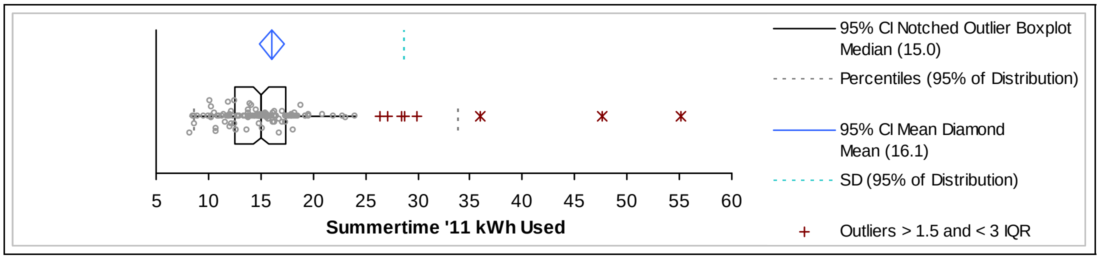
The summer of 2011:

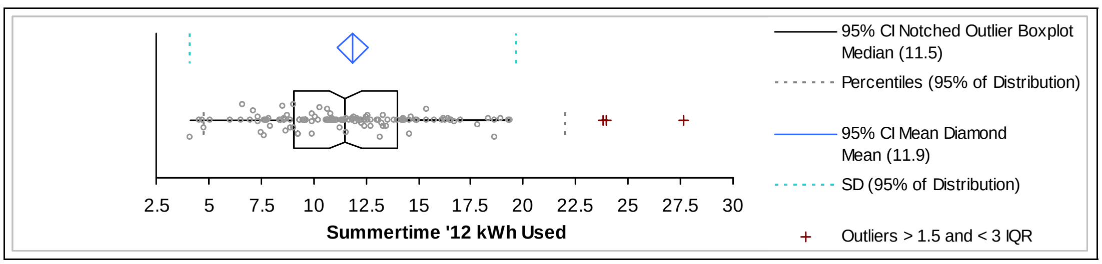


And the percentiles are as follows:

Percentile		
0th	8.17	(minimum)
2.5th	8.66	
25th	12.55	(1st quartile)
50th	14.97	(median)
75th	17.46	(3rd quartile)
97.5th	33.84	
100th	55.19	(maximum)

The range of daily baseline values we will use for 2011 is between 8.17 and 8.66 kWh

The summer of 2012:



And the percentiles are as follows:

Percentile		
0th	4.16	(minimum)
2.5th	4.75	
25th	9.03	(1st quartile)
50th	11.47	(median)
75th	14.03	(3rd quartile)
97.5th	22.06	
100th	27.66	(maximum)

The range of daily baseline values we will use for 2012 is between 4.16 and 4.75 kWh

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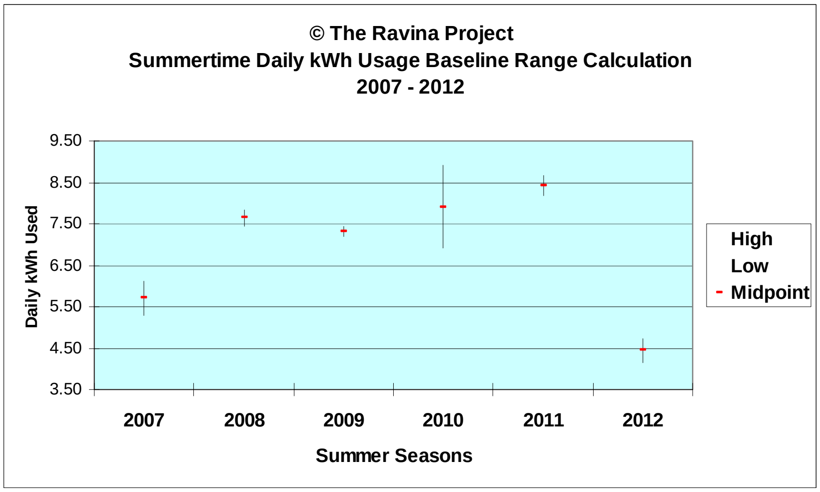
Here's the above data ranges in graphic form.



The low baseline for 2012 may be seen as suspect. What does it mean to have a household running on 4.5 kWh over 24 hours? That's 187.5 Watts on average over the period … less than running two 100 Watt light bulbs for 24 hours. I checked the raw data in our daily database and found examples like the following. On June 15th, 2012 we used 4 kWh from the Grid and sent back 4 kWh to the Grid … so from the Grid's point of view we netted out to zero usage. We generated 8.8 kWh from the solar panels … but 4 were sent to the Grid so the house ran on the remaining 4.8 kWh for the 24 hour period. We take the meter readings at the close of the generation day always, summer or winter, and we compensate for the differing read times (always in EST) in the usage database calculations.

So what's using the energy? The biggest user of energy is the fridge and in the summertime the ambient temperature around the fridge is greater than in the winter so it probably pulls more power than in the winter. It is new, modern and well insulated. Its door is opened more during the daytime than at night as well. There is little or no daytime lighting used in the summer and with an extended day the time between sun down and bed time is short. Our colour TV which is ON later at night is an old tube CRT type. All our summertime lighting uses CFL technology. All the electronics are shut down at night using power bars. During the daytime there is really nothing using power except my CRT monitor, computer, network electronics, my laptop (when not doing chores outside) and occasionally, appliances in the kitchen. At night we usually sleep with the windows open and the overhead ceiling fan on its lowest setting just to move the air. We cook using natural gas and the water is heated by our natural gas boiler. The washing machine is electrically powered and I strongly suspect that those days with the lowest energy usage are days we do not wash clothes. We dry them on our back yard clothes line. With no cooling fans active there really is no other substantial electrical load. So an occasional usage of five kWh (plus or minus) for a 24 hour period is a reasonable number for this household.

Data cleaning issues

Cooling efficiency is defined as the total number of kiloWatt-hours of energy used for every Cooling Degree Day. We will explain this relationship below in greater detail. However, the point here is to underscore the importance of isolating the energy used only for cooling. We have to subtract the baselines from the actual daily recorded kWh used for each day in the season to get the amount range used for cooling only, no matter what model we employ.

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What happens to our data when we subtract the baselines from our daily kWh usage?

Using the 2.5% Method if we subtract our lowest baseline amount from the daily seasonal readings we will get at least one value of zero in the data set. If we use the value at the 2.5th percentile we will get several resulting values less than or equal to zero. What does it mean to use a negative number of kWh in a day to cool the house?

Note that these values are interim values. The next step in the process is to generate the number of Cooling Degree Days for each day of the summer. Just like in calculating the number of Heating Degree Days in the winter by subtracting the average (Mean) daily temperature from 18 Centigrade, we use 18 C in a slightly different manner. We subtract 18 C from each daily summertime Mean temperature. The result produces the number of Cooling Degree Days (CDD) generated for each day in the summertime. For instance, if the Mean temperature for the day is 24.5 C, we calculate the CDD value as follows: 24.5 minus 18 equals 6.5 CDDs.

So let's calculate the house efficiency using 6.5 Cooling Degree Days. Suppose we use 13.0 net kWh that day for cooling. Our efficiency is calculated as net kWh/CDD or 13.0 divided by 6.5 equals an efficiency of 2.0 kWh/CDD. This means we used 2 kWh to cool the household for each degree above 18.0 Centigrade on average over the whole 24 hour day.

So far so good … what could possible go wrong with simple subtraction followed by simple division? Well, evidently lots!! Consider a day which has a negative number of CDDs. On these days the Mean temperature for the 24 hour day is less than 18 C. This is a problem because the day is technically a Heating Degree Day but it lies within the time of the year which we associate with Cooling Degree Days (CDDs). We end up with negative CDDs generated for that day.

What do we do with negative numbers?

And further, there are other issues. The denominator of the efficiency calculation may be very small. It may approach zero. In this case the resulting fraction with any kind of positive number as the numerator may get very large. We are left with monstrously large numbers for efficiency. What does it mean to have an efficiency of 5 kWh for every CDD … especially when the efficiency data are grouped around, let's say, 1.7?

So we have two situations (negative numbers and large positive numbers) where anomalous data can play havoc with our analysis. There really does not seem to be any way to make these outliers 'fit' into the data set. They are real data but their outlier status will colour our statistical results.

We will eliminate all these data from our data sets. Our efficiency calculations will be completed with existing data but any value of zero or less and any value of 4.0 or more will be eliminated. Still 4.0 kWh per a CDD is a lot of energy to cool that 1 degree. It may be too large but we'll go with it in this paper. In subsequent papers we may revise it.

Note as well, that we will use these same data cleaning methods with the datasets we generate using the other two methods (the 18 C and Inspection) for calculating baseline energy usage.

So our data cleaning method is as follows:

- Delete all negative or zero efficiencies
- Delete all efficiencies greater than or equal to 4.00

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Calculating Efficiencies

We use the following steps to calculate daily efficiencies for each of the 6 summers in our database across all three methods:

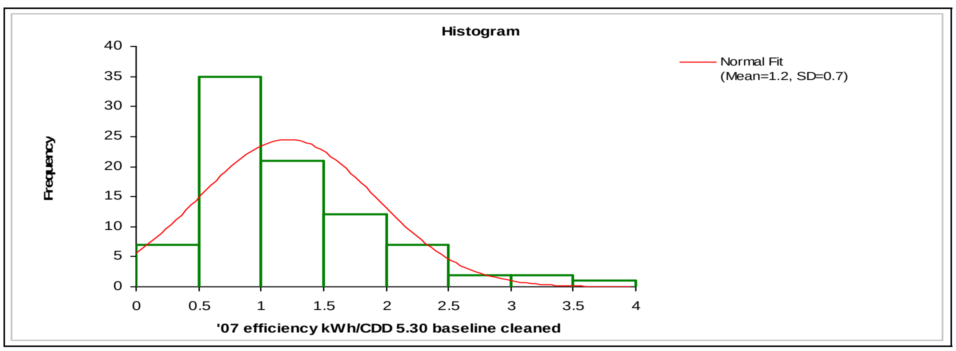
- Assemble the values for each 24 hour day: the kWh used and, from Environment Canada, the Mean temperature in C
- For each day calculate the total number Cooling Degree Days generated
- Subtract the high baseline value from each daily kWh total to calculate the lowest daily (net) kWh used for cooling
- Subtract the low baseline value from each daily kWh total to calculate the highest daily (net) kWh used for cooling
- Using these two daily cooling kWh lists described above, for each calculate a daily cooling kWh/CDD efficiency
- Sort and clean each of the efficiency lists according to the rules above
- Use our stats package to generate reports by cooling season

Our cooling efficiency ‘bracket’ values are produced below.

Note again that our method tries to ‘bracket’ the correct value for the household’s cooling efficiency. We do not have the ability to calculate an exact value but we believe we do have enough high fidelity data to ‘bracket’ the correct value according to the logic we presented earlier in the paper.

Summer of 2007 using low Baseline of 5.30 kWh per day, 2.5th Percentile Method

Here are the efficiency calculations for one year using both baselines. After this example we will place the values in a chart.



n	87	
Mean	1.211	
95% CI	1.060	to 1.361
SE	0.0758	

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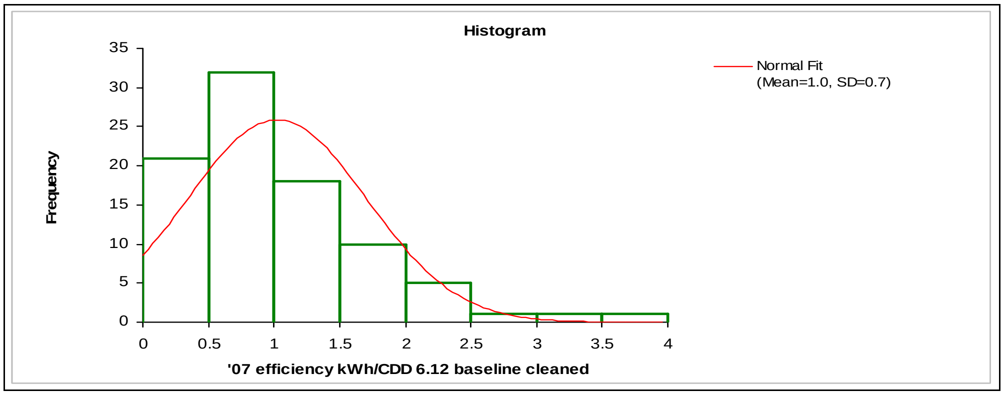
Summer of 2007 using high Baseline of 6.12 kWh per day, 2.5th Percentile Method

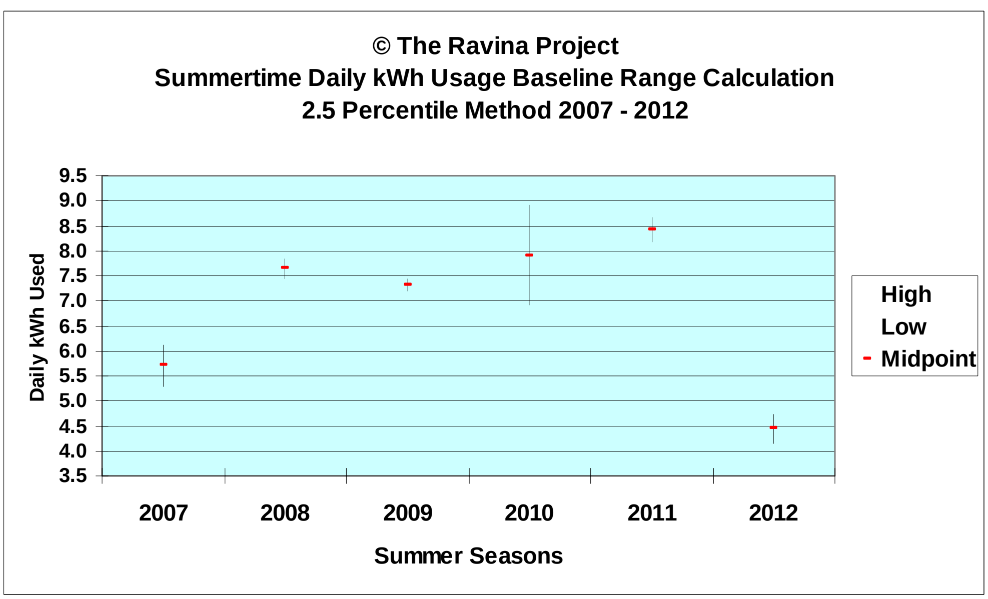


n	89	
Mean	1.023	
95% CI	0.878	to 1.168
SE	0.0728	

As you can see using a slightly larger value for the baseline makes the household look more efficient. Note as well that the number of days in the database is different for each baseline value. This is the result of the data cleaning algorithm outlined above.

Six Year summary Graphs for the 2.5% Method

As you recall from above we used the minimum daily kWh usage value for each season as our low baseline value and the value at the 2.5th percentile as the high baseline value. This graphic below shows each of these seasonal values in a range.



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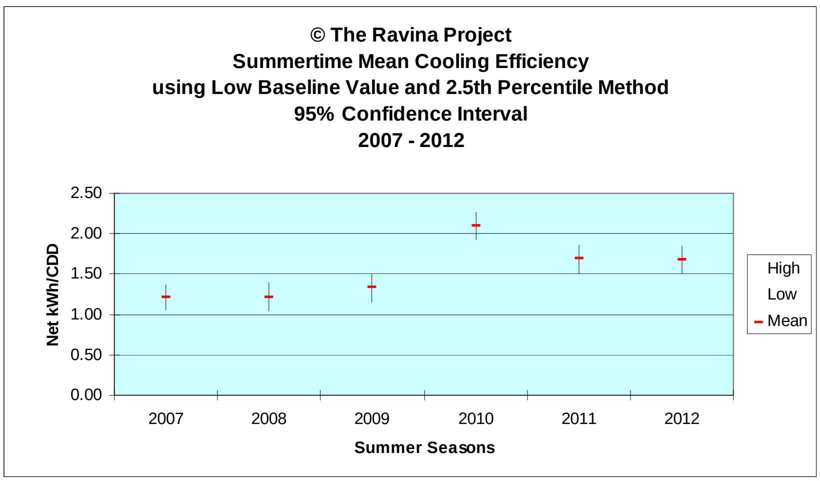
So all this work for this method comes down to the following two graphs. Each graph is based upon a different baseline value. The Mean value for each season is the red bar and the 95% Confidence Interval is plotted as a range around it. The confidence Interval is simply the range of values the Mean might be equal too. In fact the 95% Confidence Interval indicates that the Mean has a 95% chance of being in this range, 19 times out of 20.

The first chart and graph using the low baseline we isolated from our daily kWh usage during each summer cooling season.

Mean Efficiency using low baseline 2.5% Method			
Season	**Mean**	**Low**	**High**
2007	1.21	1.06	1.36
2008	1.21	1.04	1.39
2009	1.33	1.15	1.51
2010	2.09	1.93	2.26
2011	1.69	1.51	1.86
2012	1.68	1.51	1.85



The first chart and graph using the high baseline we isolated from our daily kWh usage during each summer cooling season.

Mean Efficiency using high baseline 2.5% Method			
Season	**Mean**	**Low**	**High**
2007	1.02	0.88	1.17
2008	1.15	0.96	1.35
2009	1.23	1.05	1.42
2010	1.72	1.54	1.90
2011	1.58	1.40	1.76
2012	1.57	1.40	1.74

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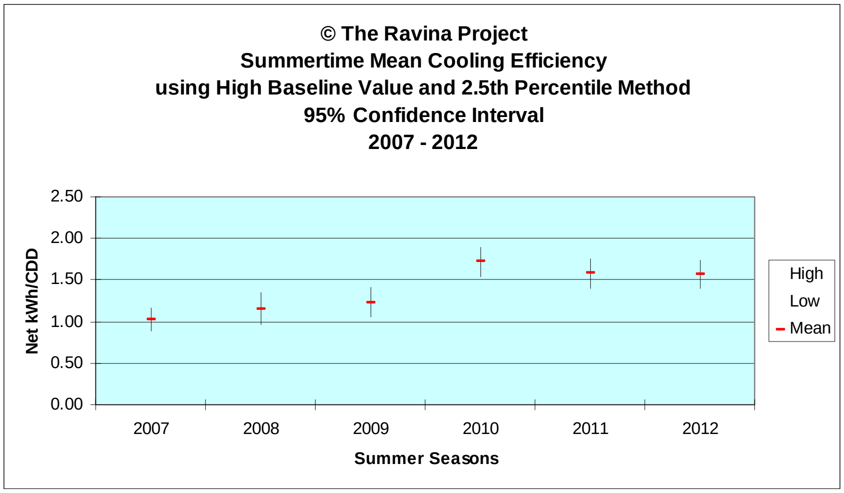

The summertime cooling has been a work in progress in a sense that each year we try to do a better job. The sun shields were new in 2011. During the last two years we have worked to cool the house using a method. And last year (2012) we adhered to strict guidelines in our efforts.

We are surprised that our data shows some consistency using this model from year to year given our baseline values were diverse. Our method of selecting a range of baseline values seems to be reasonable, that is, the cooling efficiencies do not show the same diversity. We believe we have found a household 'sweet spot' in our efforts to increase our air density without using excessive energy. More summertime data is needed to show any trends and demonstrate our regimen used for summertime cooling is effective.

Bottom line, with the data we have today, and using this method of calculation, our cooling efficiency lies between a low efficiency value of **1.86 kWh/CDD** and a high efficiency value of **1.40 kWh/CDD** for the last two summers across both baselines.

There are issues with the 2.5^{th} % method of calculation the household baseline. Since we are using the lowest kWh usage and usage at the 2.5^{th} percentile, we might be using statistical outliers on the low end for our baseline. This would skew our results.

Calculation of summer daily Baseline using the 18 C Model

The main benefit of this model is that we don't have to make an arbitrary decision about what numbers to use. We will let the stats package give us those numbers.

So to unpack this chart below, each year the days within our temperature range (18 C +/- 2.5 C) have the Mean value for the number of kWh used just to run the household. Notice that 2010 and 2011 have Means quite different that all the other years. One can account for this difference if the household is taken into consideration. There was one more person living in the house during these years. All other years had two people in the household. This is another example of how the household make-up affects the household thermodynamics.

The next step now is to use these baseline values to isolate the kWh used each day to cool the house, assemble the Cooling Degree Days for each day, calculate the daily cooling efficiency, clean the data and crunch the numbers for each season based upon the high and low baseline.

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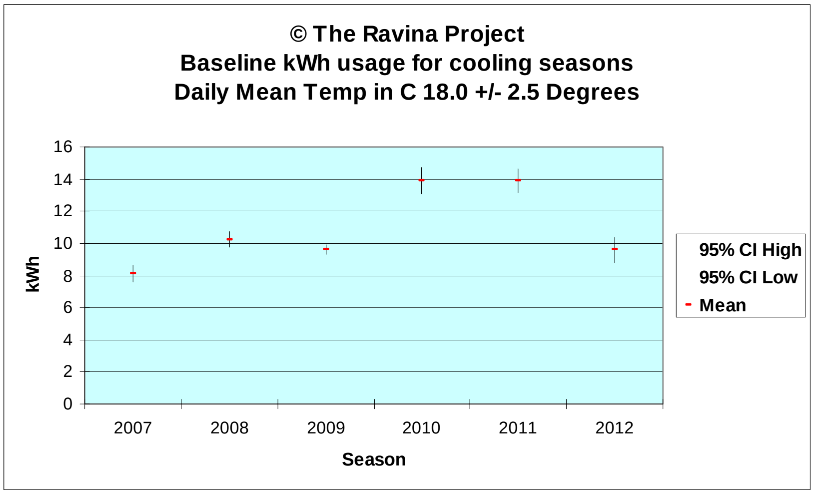
Summertime 2007-2012 kWh Baseline temp <=20.5 and >=15.5 C			
Season	**95% CI High**	**95% CI Low**	**Mean**
2007	8.66	7.58	8.12
2008	10.74	9.75	10.24
2009	9.89	9.28	9.58
2010	14.69	13.06	13.88
2011	14.64	13.11	13.88
2012	10.35	8.81	9.58

Here is the chart above in graphic form.



The two years of three person summertime household status sure stick out when looked at in graphic form. Note they also show how regular the household response is during other seasons when the house occupancy is limited to two.

Efficiency Calculation using the 18 C Method

Consider the following chart.

Summertime 2007-2012 efficiencies based upon temp - high Baseline			
Season	**95% CI High**	**95% CI Low**	**Mean**
2007	1.12	0.52	0.82
2008	1.43	0.47	0.95
2009	0.20	0.11	0.15
2010	0.27	0.20	0.24
2011	0.22	0.14	0.18
2012	0.26	0.20	0.23

Using this baseline there seems to be a break between 07-08 and subsequent years. As well, the highs and lows are grouped more tightly around the last 4 years than the first two.

This grouping will be most obvious in the following graphic of the above chart.

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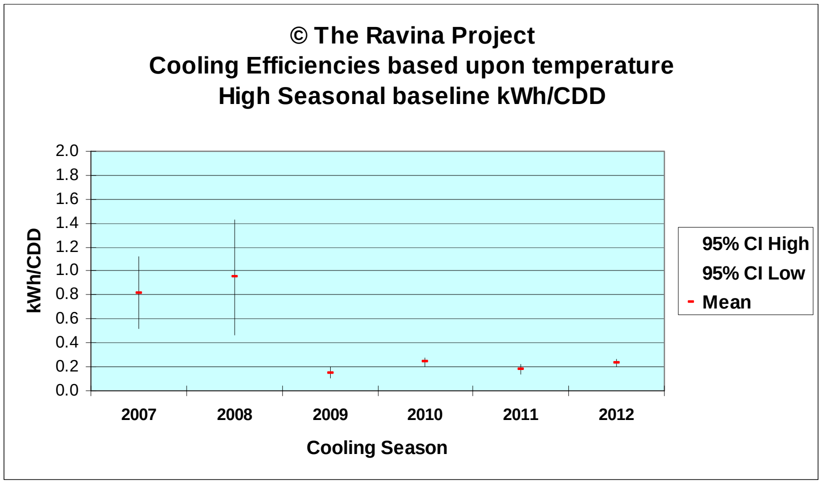
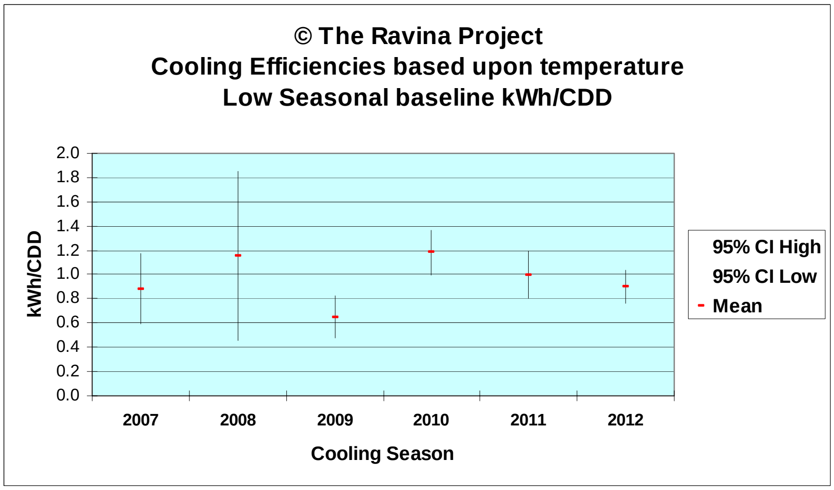
For some reason this look at the last 6 cooling seasons indicates that, by this baseline, we have been somewhat consistent in our efforts in employing energy to cool the household.



Let's look at the same years using the low baseline which allocates more kWh each day for cooling and less to run everything else in the household.

Summertime 2007-2012 efficiencies based upon temp - low Baseline

Season	95% CI High	95% CI Low	Mean
2007	1.17	0.59	0.88
2008	1.85	0.46	1.15
2009	0.83	0.48	0.65
2010	1.37	1.00	1.19
2011	1.20	0.80	1.00
2012	1.04	0.76	0.90



The difference in the last 4 years is exaggerated somewhat as compared to the efficiency calculation based upon the high baseline kWh value.

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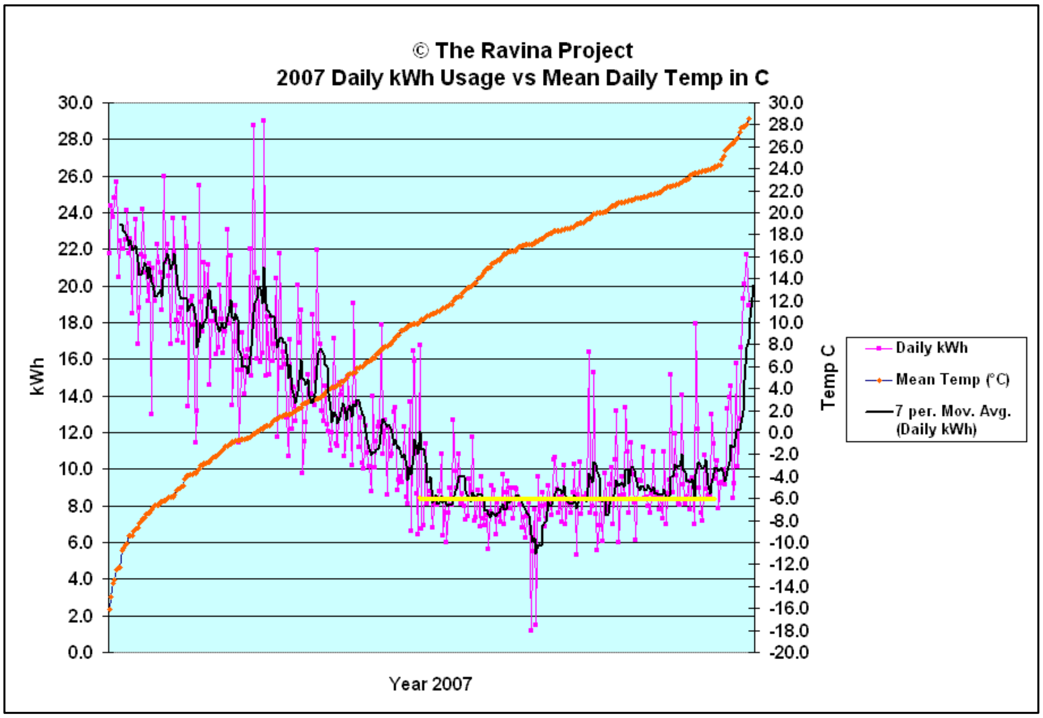
Calculation of summer baseline using Inspection Method

This model will require us to look directly at the data and inspect it for baseline values. The graphic below needs to be unpacked for clarity. It graphs every day in 2007 but it sorts the daily Mean temperature from smallest to largest on the orange line. For each of these days, the household usage of electricity is plotted on the magenta line. The black line traces the 7 day average kWh usage. It smoothes out the daily kWh line allowing us to better see rises and falls in usage. The yellow line identifies the area of the graph we are interested in, the baseline of daily electricity usage.



Just like this graph above, we will examine each year's kWh usage and identify the days which have a baseline energy usage. It looks like, above, the kWh usage we are interested in starts on days with a Mean temperature of about 10 C and continues until the daily Mean temperature is about 24 degrees C, a span of 14 degrees C.

The data from those ranges has been collected, statistically processed and charted below.

Summertime 2007-2012 kWh baseline from Inspection			
Season	**95% CI High**	**95% CI Low**	**Mean**
2007	9.78	9.09	9.43
2008	10.98	10.29	10.64
2009	10.42	9.92	10.17
2010	14.37	13.06	13.71
2011	13.96	12.88	13.42
2012	10.69	9.53	10.11

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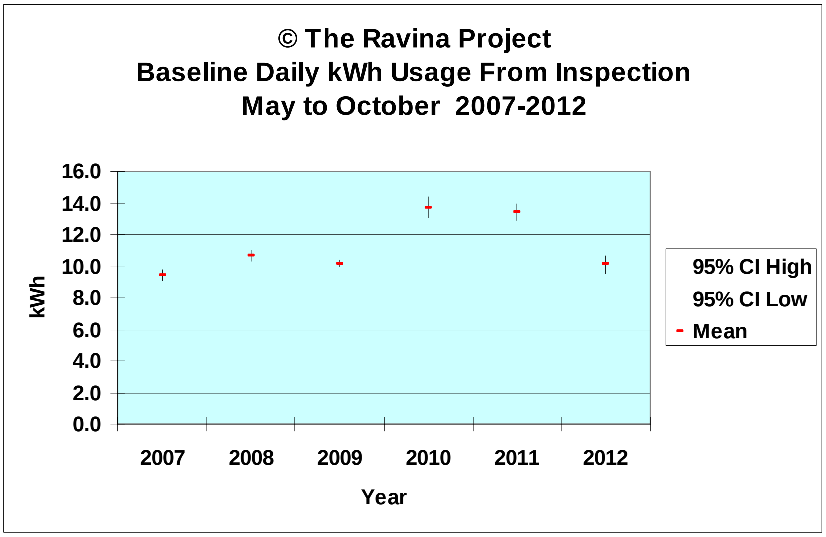
And the graphic …



We note immediately that this graph looks similar to the above graphic made from data extracted using the 18 C method. We also note how close the CI values are to the Mean.

Efficiency Calculation using the Inspection Method

The next charts show the efficiencies using the high baseline and low baseline calculated and cleaned the same way as all other data in this paper.

Summertime 2007-2012 efficiencies based upon Inspection - high Baseline

Season	95% CI High	95% CI Low	Mean
2007	1.02	0.54	0.78
2008	0.26	0.11	0.18
2009	0.36	0.10	0.23
2010	0.11	0.07	0.09
2011	1.07	0.68	0.88
2012	0.78	0.52	0.65

Summertime 2007-2012 efficiencies based upon Inspection - low Baseline

Season	95% CI High	95% CI Low	Mean
2007	0.80	0.44	0.62
2008	0.23	0.11	0.17
2009	0.27	0.08	0.18
2010	0.11	0.07	0.09
2011	1.18	0.81	1.00
2012	0.94	0.67	0.80

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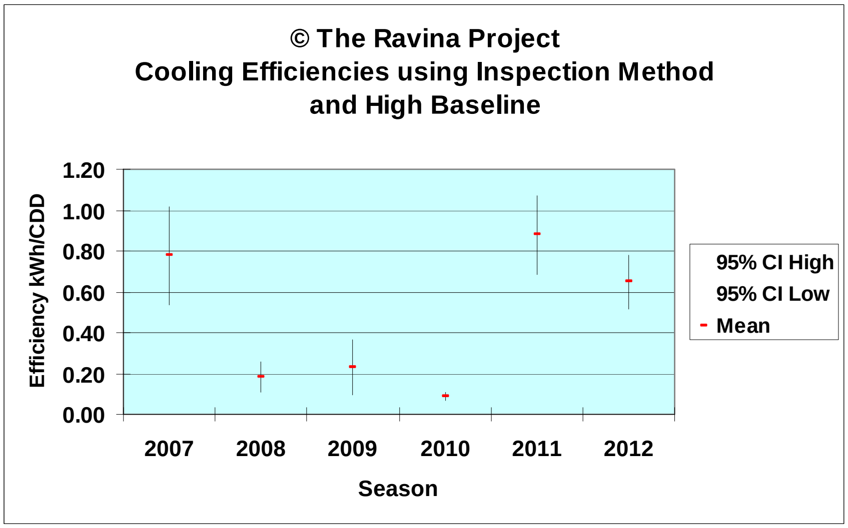
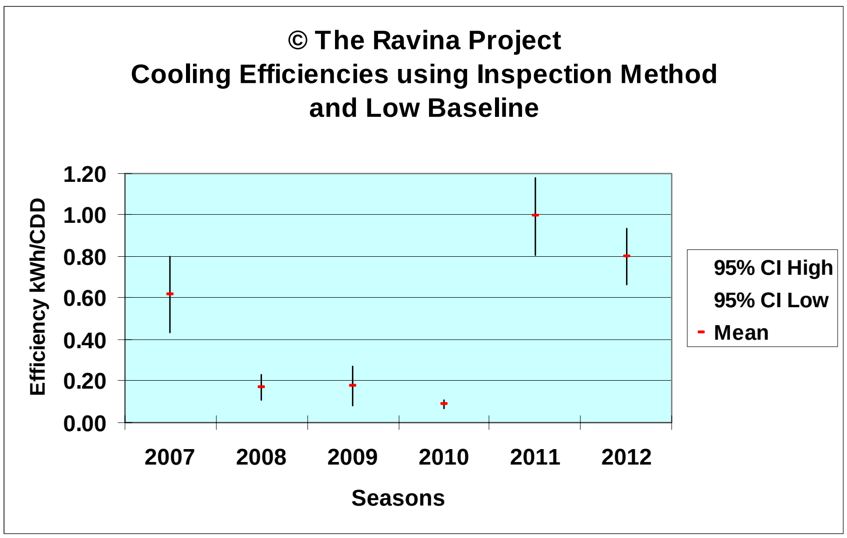
And the graphics





Our household cooling efficiency using the Inspection Method is anywhere from **0.10** to **1.20** kWh used for each Cooling Degree Day for all summers between 2007 and 2012.
If we look just at the last year, 2012 when we put all our ideas regarding household cooling into play, our efficiency lies between **0.50** and about **0.90** kWh used for every Cooling Degree Day using this Method.

Consolidation of the Three Models of Efficiency Calculations

Let's consolidate our findings into a chart and graphic. We have taken just the Mean values for each method for each season for each baseline.

Summertime 2007-2012 Efficiencies Compared High Baseline Means			
Season	**2.5th % Method**	**18C +/- 2.5C Method**	**Inspection Method**
2007	1.02	0.82	0.78
2008	1.15	0.95	0.18
2009	1.23	0.15	0.23
2010	1.72	0.24	0.09
2011	1.58	0.18	0.88
2012	1.57	0.23	0.65

Summertime 2007-2012 Efficiencies Compared Low Baseline Means			
Season	**2.5th % Method**	**18C +/- 2.5C Method**	**Inspection Method**
2007	1.21	0.88	0.62
2008	1.21	1.15	0.17
2009	1.33	0.65	0.18
2010	2.09	1.19	0.09
2011	1.69	1.00	1.00
2012	1.68	0.90	0.80

Just from the data we see that the 2.5th percentile method shows the household as consistently less efficient that the other two methods. Our suspicions that the 2.5th % method is really latching on to outliers at the bottom of the statistics, meaning that they would allocate a very minimum to the household net of cooling energy used, seem to be correct.

The graphics for the two above charts show the relationship between the Means from each method. We see that consistently, the 2.5th percentile method allocates too much energy to household cooling which we could infer from the charts above but becomes even more explicit as we view the graphics.

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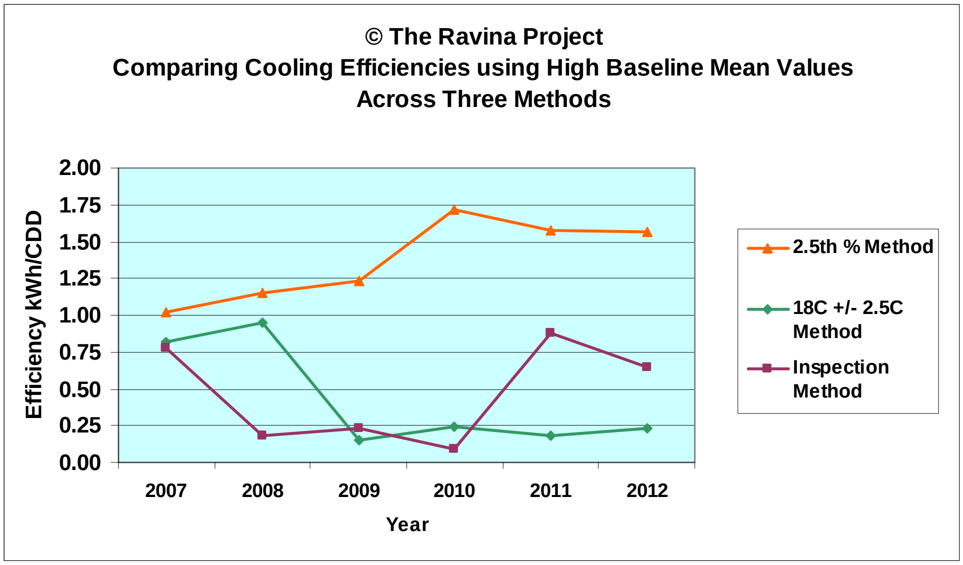

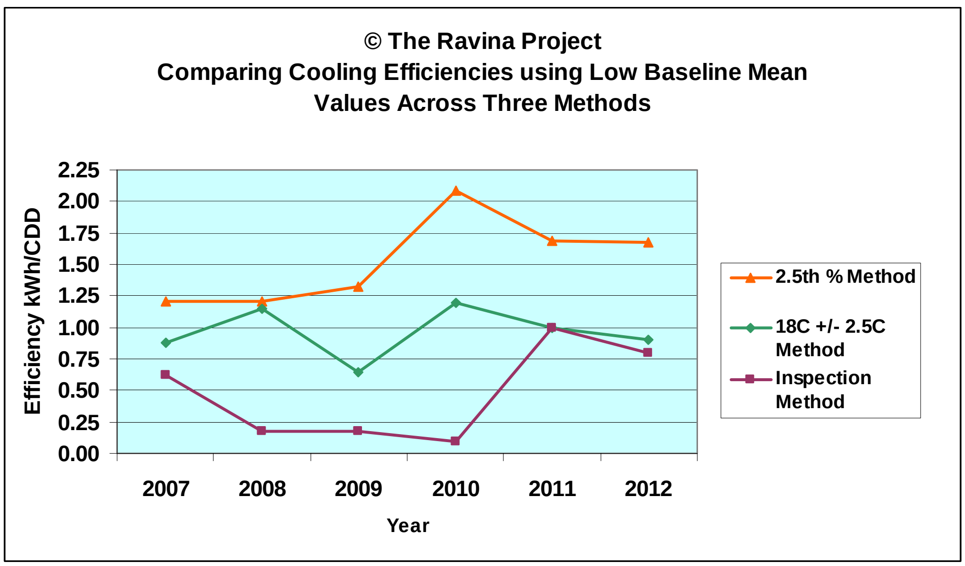

This section of the paper turned out to be as much about summertime cooling efficiency calculation methodology as an attempt to calculate our household cooling efficiency. It's quite a problem as stated earlier in this paper since we use electrical energy to both operate the household and cool it. The 2.5th percentile method seems to be the odd man out in this paper so far. The other two methods are much more closely related with respect to the range of values for household cooling efficiency.

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Evaluating the Cooling Efficiency Calculation Methods

So which of the three methods of calculation and the two baselines for each, is the best and most accurate calculation for the baseline and household seasonal efficiency?

Our data includes the total amount of kWh we used each day. We also gather the Mean temperature for each day from Environment Canada (our tax dollars at work). For the season we have calculated the baseline range across three different methods. We can calculate the number of Cooling Degree Days for each day. We can therefore, theoretically, construct the formula that will use at its starting point the daily Mean temperature and predict the number of kWh we used in the day and for the season as a whole.

The algorithm proceeds as follows for each day across three methods and two baselines:

1. from the Mean daily temp calculate the number of Cooling Degree Days
2. multiply the value of the CDD and the two Mean seasonal cooling efficiencies to give two values for the kWh used on that day due to household cooling efficiencies.
3. add in the baseline amount of kWh to each total. The high Baseline is added to the daily total calculated with the high Baseline Mean seasonal efficiency and the low with the low.
4. do this for each of the methods, their seasonal Mean efficiencies and their high and low Baseline values.

The output of this algorithm is the number of daily kWh used that season and a table of daily values for each method/baseline per season. We also have the actual values we recorded for each day and totals for the season. We have all the data required to evaluate on a daily and seasonal basis how close our methods are to realty.

Here's a chart of the three methods and two baselines for each:

kWh Used Seasonal Predictions v.s. Actual as Percentage

Seasons	2.50% Low Baseline	2.50% High Baseline	18 C High Baseline	18C High Baseline	Insp High Baseline	Insp High Baseline
2007	3.04%	3.05%	11.43%	19.48%	15.24%	28.76%
2008	0.95%	2.44%	18.74%	21.04%	-6.83%	-2.33%
2009	5.03%	4.74%	6.68%	-0.94%	0.15%	6.31%
2010	-5.75%	-4.51%	4.01%	-12.56%	-25.58%	-18.36%
2011	1.42%	1.36%	12.99%	-1.04%	11.52%	14.95%
2012	2.12%	2.27%	7.53%	-7.52%	9.22%	12.39%
	First	Second	Third			

To unpack this chart, the numbers are the seasonal predicted numbers as a percentage of the actual numbers. For instance the 2.5% Low Baseline prediction of the kWh used in 2007 was off by 3.04% from the actual number of kWh used. The numbers in green are the best with orange numbers coming in third. As you can see the 2.5% method is the first overall with the low baseline just besting the high baseline.

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So which of the methods / baseline pairs predicted the closest data to the original data? That is, on a day by day basis which of the methods predict a data set very close in magnitude on a day by day basis. The Altman Bland test shows the bias of the predicted data set when compared to the actual daily collected data. Less than a 2% bias is really good. The 2.5% Low Baseline data set is very close on a day by day basis for several years. When all the cooling days for six summers are taken into consideration, the 2.5% Low Baseline predictions are very close on a day by day basis compared to the actual daily amounts used.

kWh Used Seasonal Predictions v.s. Actual Altman Bland Test % Bias

Seasons	2.50% Low Baseline	2.50% High Baseline	18 C High Baseline	18C High Baseline	Insp High Baseline	Insp High Baseline
2007	2.7	4.0	12.8	20.1	17.1	27.7
2008	1.9	3.6	18.6	21.0	18.6	21.0
2009	4.3	4.4	8.1	1.5	2.6	8.4
2010	-6.3	-3.2	7.2	-8.7	-24.3	-15.3
2011	2.0	2.4	15.1	2.9	13.8	17.0
2012	1.4	2.4	11.2	-2.3	13.0	16.2
2007-12	1.0	2.3	12.2	5.9	7.2	12.9
p-value	0.3623	0.0323	< 0.0001	< 0.0001	< 0.0001	< 0.0001
	First	Second	Third			

And now for the total for the six years. How well did the various method / baseline groups do in predicting the actual number of kWh used across the six summers given the Mean daily temperature?

Predicted kWh Usage Values for each Method over Summer 558 Days

	Actual	2.5% Low Baseline	2.5% High Baseline	18 C Low Baseline	18 C High Baseline	Insp Low Baseline	Insp High Baseline
Total kWh	**7301.17**	**7343.45**	**7377.47**	**8030.14**	**7402.64**	**7526.49**	**7946.71**
% Difference	**0**	**0.58%**	**1.03%**	**9.08%**	**1.37%**	**2.99%**	**8.12%**
Correlation Coefficient		**0.73**	**0.74**	**0.75**	**0.59**	**0.53**	**0.56**

We see that the 2.5% Low Baseline just beats out its High Baseline mate by about 0.5%. The 2.5 % Method seems to be the best one to use to predict how much energy the house will use given the Mean 24 hour daily temperature.

We will do more work on this to try to generalize this method.

So bottom line for this section of the paper, we can develop models for cooling energy usage isolation thereby allowing us to calculate our household cooling efficiency. We can use the output from these models to predict our household energy usage across a seasonal and multi-year span.

Since our house is a common design in Toronto we would like to explore how much of our work / methodology can feed into a general thermodynamic model for this type of house.

We hope others can take this work and expand it into practical models to be used in the community.

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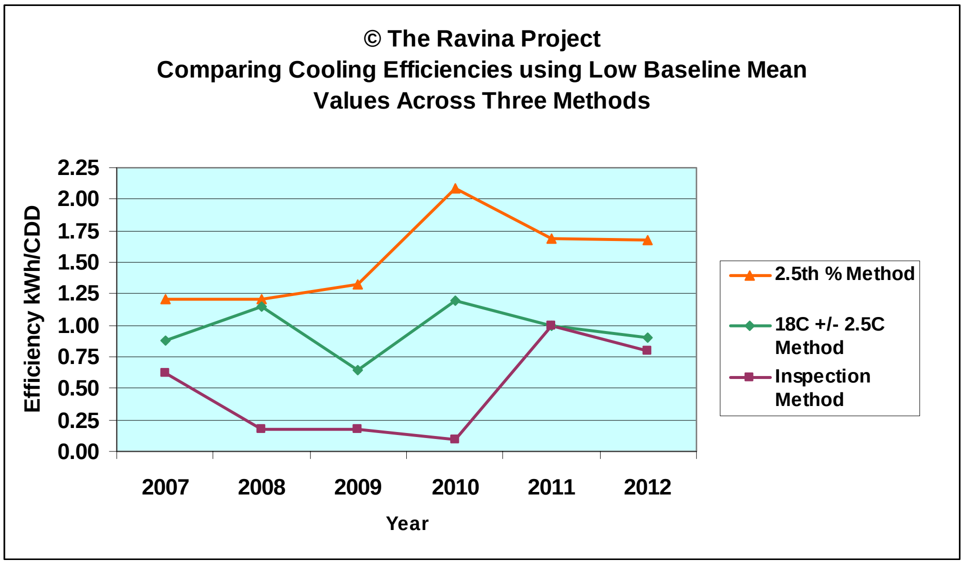
Household Cooling Efficiency

To get back to the top of the paper, what is our household cooling efficiency? We have crunched the numbers and found that the 2.5th Percentile method's Mean efficiency using the Low Baseline is the most accurate.



We can then say with a degree of confidence that our household efficiency is somewhere between about **1.2 and 2.1 kWh/CDD** according to the graph above across the past 6 summers.

This concludes this section of the paper.

Household Response to Heat and Humidex

For this section of the paper we want to get some idea of how the household responds to heat and Humidex over the summer to 2012. We choose 2012 because we used all our non-Air Conditioning cooling techniques over the whole season. We had a gradual approach to comfort such that we employed more and more energy on a marginal basis to maintain our comfort level. However, we were not shy about using extra energy. In other words we did not suffer discomfort for 'the cause' as it were. We're too old for that. We will repeat the experiment next summer as well. Hopefully over the course of several summers we can build up a baseline response to both heat and Humidex.

So the questions for this section of the paper are:

- **What is the household response to heat?** As the days get hotter how much more energy do we use? Do we use gradually more energy to cool the house or is there a temperature point where household energy demands rise dramatically?
- **What is the household response to Humidex?** As the days get more humid how much more energy do we use? Do we use gradually more energy to dehumidify the house or is there a Humidex temperature where household energy demands rise dramatically?

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Creating our Summertime Database for Heat and Humidex

To create a database to analyze we use Environment Canada data from Pearson International for our calculations.

Each day in the summertime falls into four different categories. That is, each day provides a datum in each of four databases. So what are these databases?

Each day provides a datum for:

1. maximum temperature,
2. average temperature,
3. maximum Humidex,
4. average Humidex.

Calculating Values using Environment Canada's Data

We get our detailed hourly values from Pearson International. They look like the following for one 24 hour period except for Humidex, that's a calculated value:

Date/Time	Temp (°C)	Dew Point Temp (°C)	Humidex
8/1/2012 0:00	20.9	18.4	27.2
8/1/2012 1:00	20.1	17.0	25.4
8/1/2012 2:00	19.7	17.1	25.1
8/1/2012 3:00	19.5	17.4	25.1
8/1/2012 4:00	19.8	17.5	25.4
8/1/2012 5:00	19.6	17.4	25.2
8/1/2012 6:00	20.5	17.7	26.3
8/1/2012 7:00	21.1	18.3	27.3
8/1/2012 8:00	22.6	19.0	29.4
8/1/2012 9:00	23.8	18.9	30.5
8/1/2012 10:00	25.1	17.8	31.0
8/1/2012 11:00	25.9	17.4	31.5
8/1/2012 12:00	26.5	16.7	31.6
8/1/2012 13:00	27.2	17.0	32.5
8/1/2012 14:00	27.1	16.2	31.8
8/1/2012 15:00	27.6	16.9	32.8
8/1/2012 16:00	27.3	16.2	32.0
8/1/2012 17:00	27.3	15.9	31.8
8/1/2012 18:00	26.5	15.3	30.7
8/1/2012 19:00	25.3	14.8	29.2
8/1/2012 20:00	23.9	14.3	27.4
8/1/2012 21:00	23.4	14.0	26.8
8/1/2012 22:00	22.4	12.7	25.0
8/1/2012 23:00	21.8	14.0	25.2

These values are imported into a spreadsheet where it becomes trivial to calculate the average temperature and maximum temperature for that 24 hour period. We do this for each day of the 122 or so days in the whole summer, from June 1st to Sept 30th. We make the same calculations for daily Humidex.

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Calculating Humidex

The data we get comes with no Humidex value but we are supplied with all the data that are required for a Humidex calculation: the temperature in Centigrade and the dew point also in Centigrade. We must change the dew point temperature to the same value on the Kelvin temperature scale and then do the math to calculate Humidex.

We use the following set of equations from Environment Canada of make the calculation

e = 6.11 * exp(5417.7530 * ((1/273.16) – (1/dewpoint K)))
h = (0.5555)*(e-10.0)
Humidex = (air Temperature) + h

The spreadsheet math for each Humidex calculation looks like the following where B2 is the air temperature and C2 is the dew point both in Centigrade:

=B2+0.5555*(6.11*EXP(5417.753*(1/273.16-1/(C2+273.16)))-10)

For every value in the Humidex column in the spreadsheet above we execute the same set of equations. Pulling off the daily average Humidex and the daily maximum Humidex is again a trivial activity.

We now have all the data to look, statistically, at our household response to heat and humidity.

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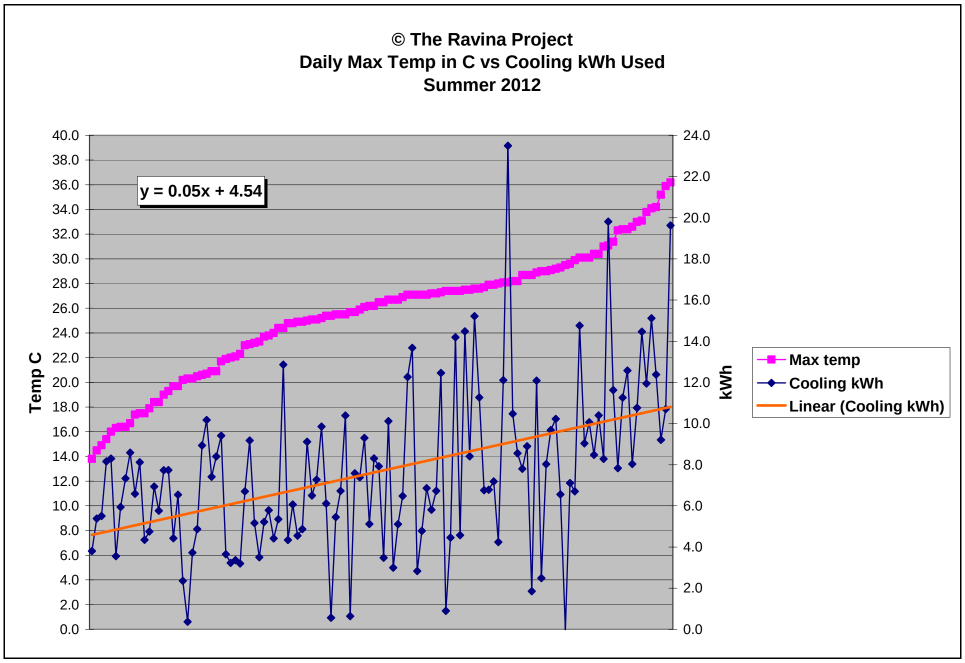
Household response to Heat

The following graphs provide some insight into how the household responded over this last summer to the daily maximum temperature.



This graph is ‘busy’ like the graphs that follow but they are all constructed the same way. For this first one we’ll unpack it in detail so the explanations for the others can be less detailed.

The magenta data points are the daily maximum temperatures sorted smallest to largest. Their value can be determined by using the temperature scale on the left.

The blue data points are not sorted. They represent the energy in kiloWatt-hours used for each day in the magenta line. That is they are paired up with the daily maximum temperature data points. Their value can be determined by the scale on the right.

So for example, the day that had the lowest maximum temperature on the graph looks like has a temperature of between 13.0 and 14.0 degrees C … maybe 13.5 C or so? So how much energy was used that day to cool the house? We see that the energy used was about 4.0 kWh. All the other temperatures are locked together with the energy used each day in the same way.

The orange line is a straight line that tells us whether the energy used to cool is increasing or decreasing in value as the daily maximum temperature increases. It encapsulates the household response to increasing maximum daily temperatures over the whole summer. As you can see the daily use of energy for cooling increases. The line’s equation is calculated and appears in the window. The important thing to notice about this equation is that value for ‘x’ or as we will call it, the ‘slope’. If the slope is zero then the line would be horizontal. That would mean that as the daily maximum temperature increased the household did not respond by using more energy for cooling. That situation is highly unlikely.

This graph demonstrates the household reaction to increasing daily high maximum temperatures. It also demonstrates a layered approach to household cooling. With so many devices on hand to help cool the household, as each is employed in the cooling effort, a small additional amount of energy is used for cooling. As we see the slope is positive which means that the line tilts up. So in

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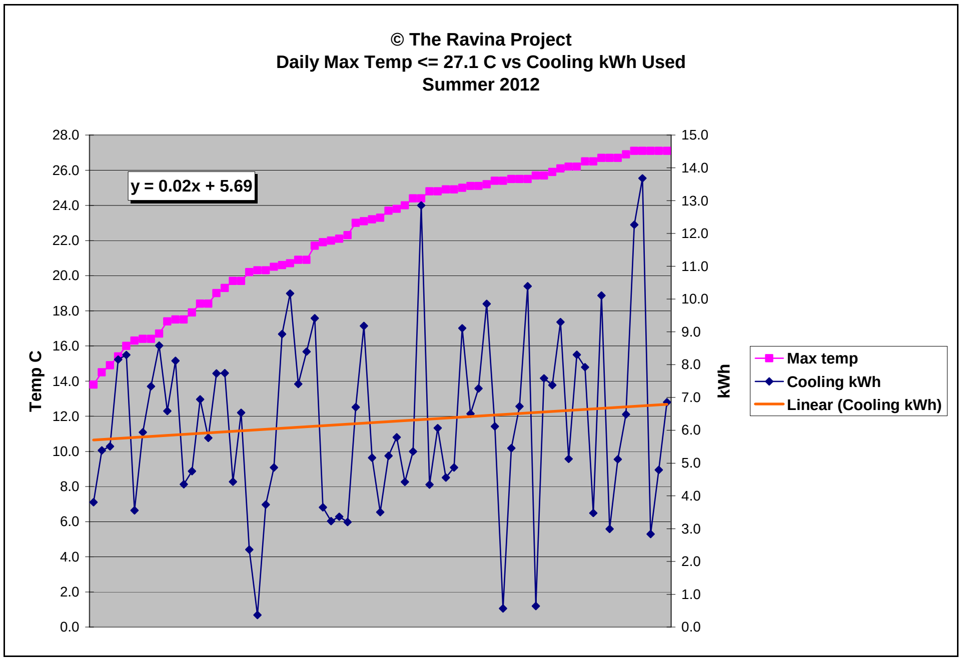
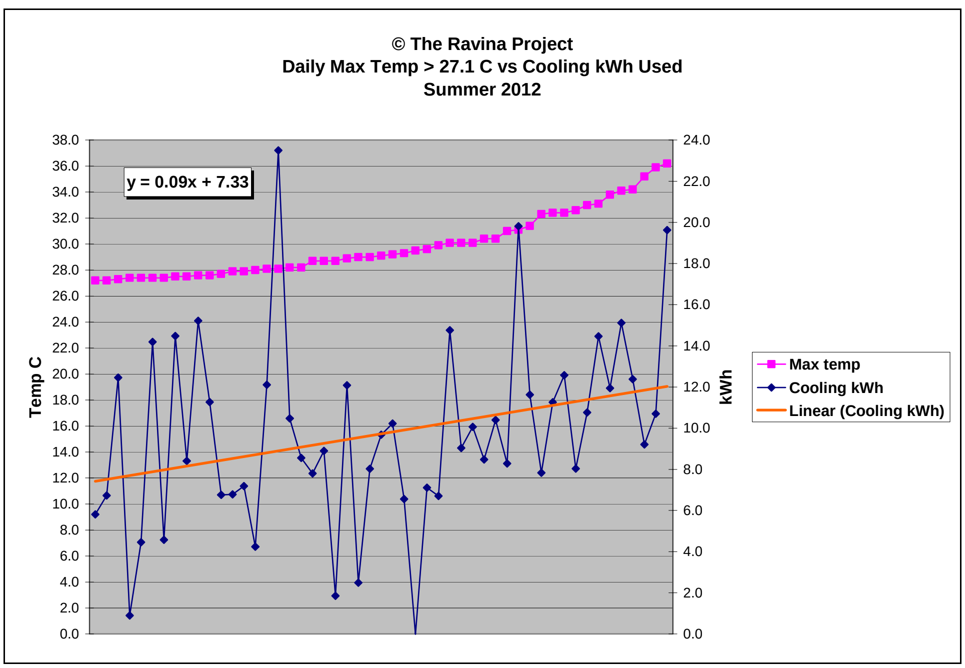
this case the slope of the line is 0.05 for whole summer. If we look closely we see that the cooling kWh responds to increased maximum daily temperature differently in the part of the graph that has a maximum temperature less than 27.1 C and different again for the part over 27.1 C.

Let's look at the graph of daily maximum temperatures less than or equal to 27.1 degrees C. Look at the slope. We see it is 0.02, which is 2.5 times less than the slope for the whole summer. This means that over this maximum daily temperature range the household energy response is much less. Extra energy used for cooling is not aggressively used.



This is just part of the season, so let's look at the other part below.



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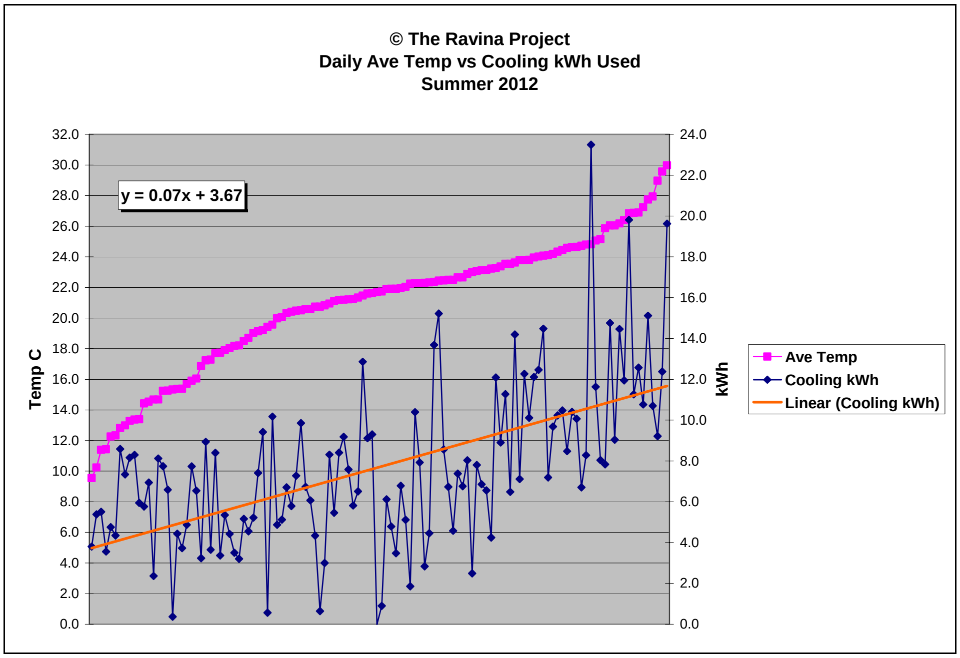
We isolated the days which have a daily maximum temperature of over 27.1 C. As we looked at the original summer-long graph we suspected that this part of the graph would have a different cooling characteristic such that we would employ more marginal energy to cool the household. It looks like our intuition is correct. Note that the slope of the orange line has increased to 0.09. The line is tilted upwards higher than our previous slope by a factor of 4.5.

The household clearly is responding by aggressively employing more cooling energy on days with hotter daily maximum temperatures, actually 4.5 times more aggressively than when the maximum daily temperature is under 27.1 degrees C.

So far, we have seen the response to daily maximum temperatures. What about daily average temperatures? One could speculate that the household would respond more aggressively to daily average temperatures because the daily average encompasses sleeping time. Days with higher daily maximum temperatures may have cooler nights. Days with high average 24-hour temperatures most probably have warmer nights.

Consider the graph below which plots daily average temperatures vs. the cooling kWh used each day.



Firstly, look at the slope or the household's seasonal response to the increase in the daily average temperature. It is 0.07 as compared to the response of 0.05 to daily maximum temperatures. It shows 40% more energy usage. Our speculation that heat at night contributes to more cooling energy used, may have merit.

This graph breaks down into two sections like the graph above. We have looked at the data carefully and discovered that the break point is a daily average temperature of 23.2 degrees C. So let's look at this same graph above but broken into two sections, one less than 23.2 and another more than 23.2 degrees C average daily temperature.

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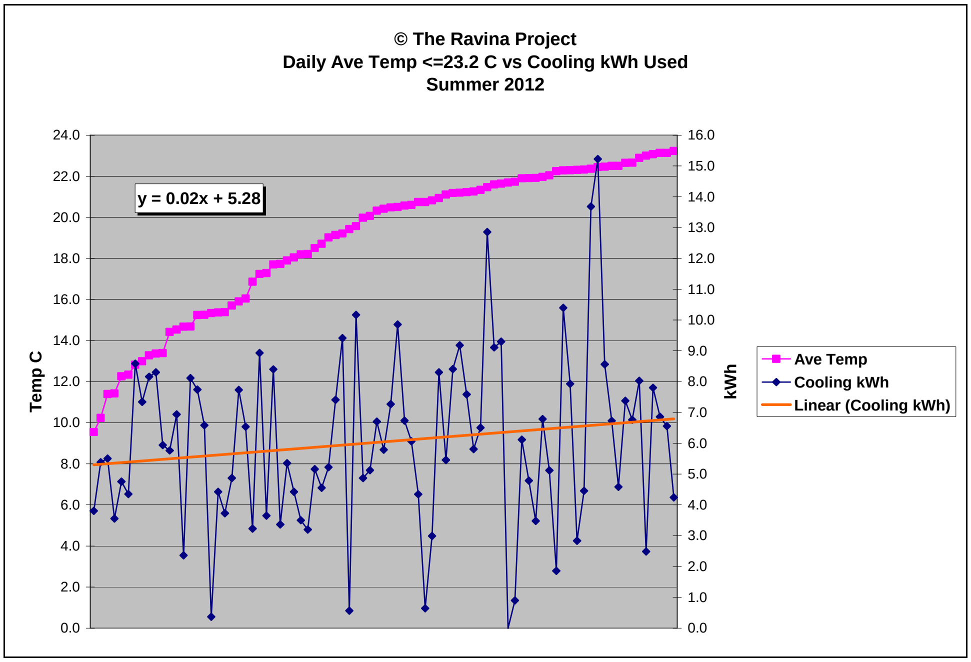
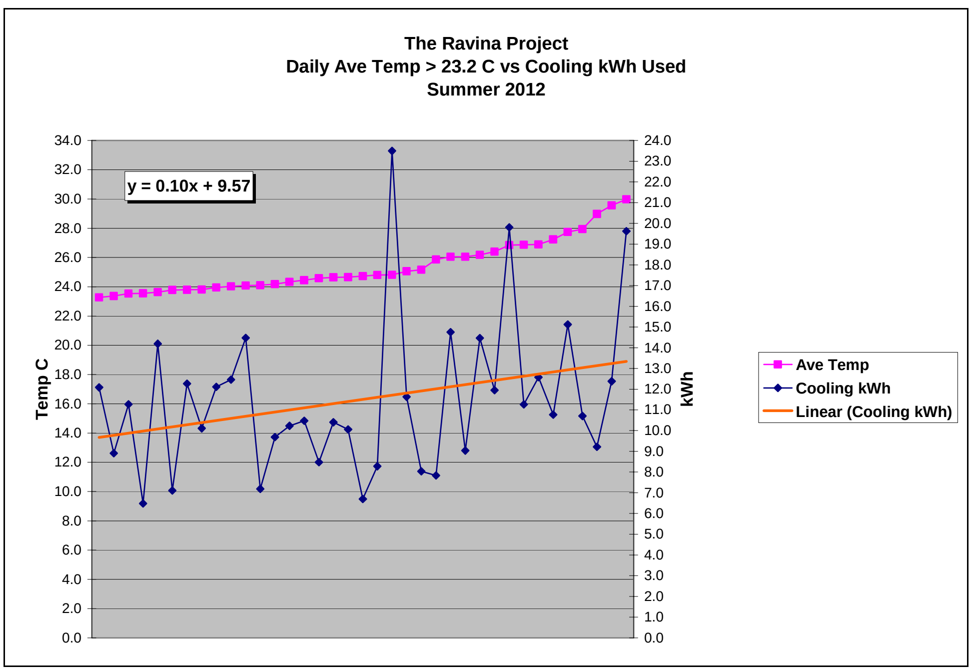


This response is identical to the graph where the daily maximum temperatures were less than 27.1 degrees … only it's about four degrees lower in temperature. We are far more sensitive to average daily temperatures than daily maximums.

Consider the graph for daily average temperatures over 23.2 degrees C



Wow! The household response to average daily temperatures is five times greater when the temperature is above 23.2 degrees C.

Our *a priori* gut feelings turn out to be true. We are much more sensitive to 24 hour average temperatures than maximum daily temperatures. The only major difference between them is the

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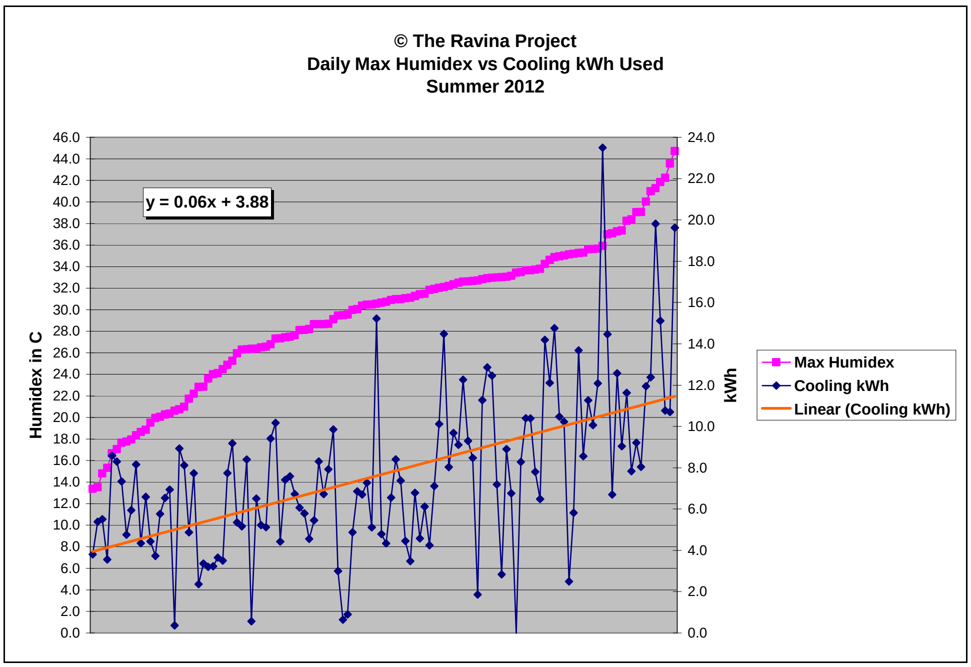
fact that overnight temperatures are taken into consideration when the 24 hour average temperature is calculated.

This fact has huge implications for CO2 pollution part of the global warming crisis. One of the fingerprints of CO2 pollution is elevated night time temperatures. This experimental data strongly suggests people may be much more sensitive to 24 hour average temperatures rather than daily maximum temperatures. This means that future average temperature estimates (climatology) must be understood as important, critical data when planning future Grid load/usage in areas where average daily temperatures are increasing.

Household response to Humidex

In this section we will look at how the household responds to increasing Humidex.

Consider the following graph:



Here we have a graph very similar to the graphs we have seen to this point. The only difference is that the magenta line represents the sorted maximum Humidex calculated for each day. All the other curves are identical to the other graphs. The orange line represents the response that the household has to the increasing Humidex by an increase in the number of kWh of energy used to cool the household.

Notice the slope is 0.06. You remember that the slope of the response line to just temperature was 0.05. So the first thing we can do is to make a comparison between heat and Humidex. We see that the household responds slightly more (20%) to daily maximum Humidex than to daily maximum heat across the whole season.

Note that this graph, like the last one on heat only, divides itself in two. Looking at the data the dividing point Humidex value is about 31.9 degrees C.

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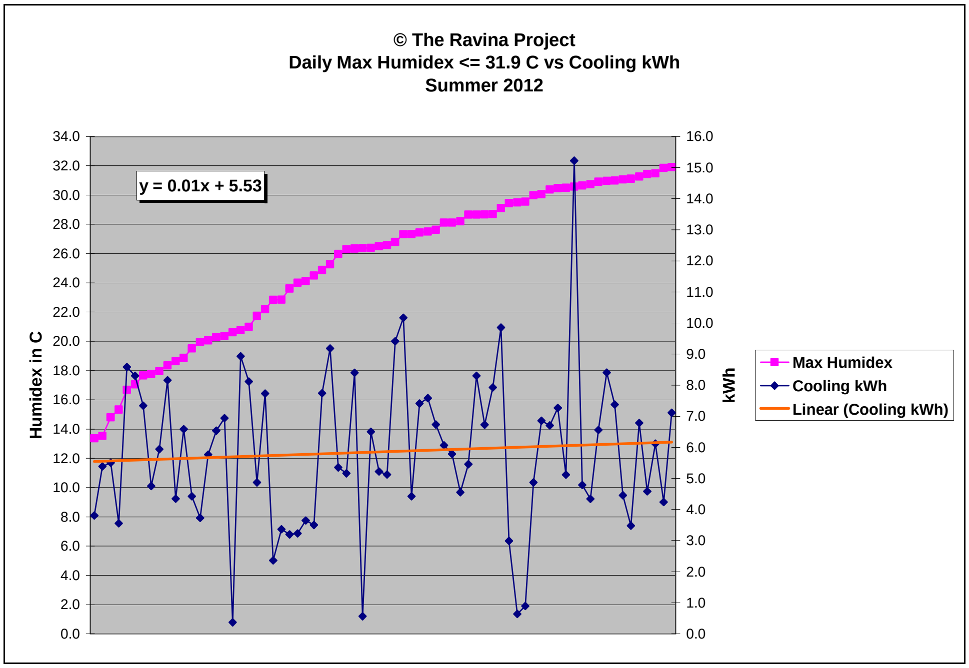
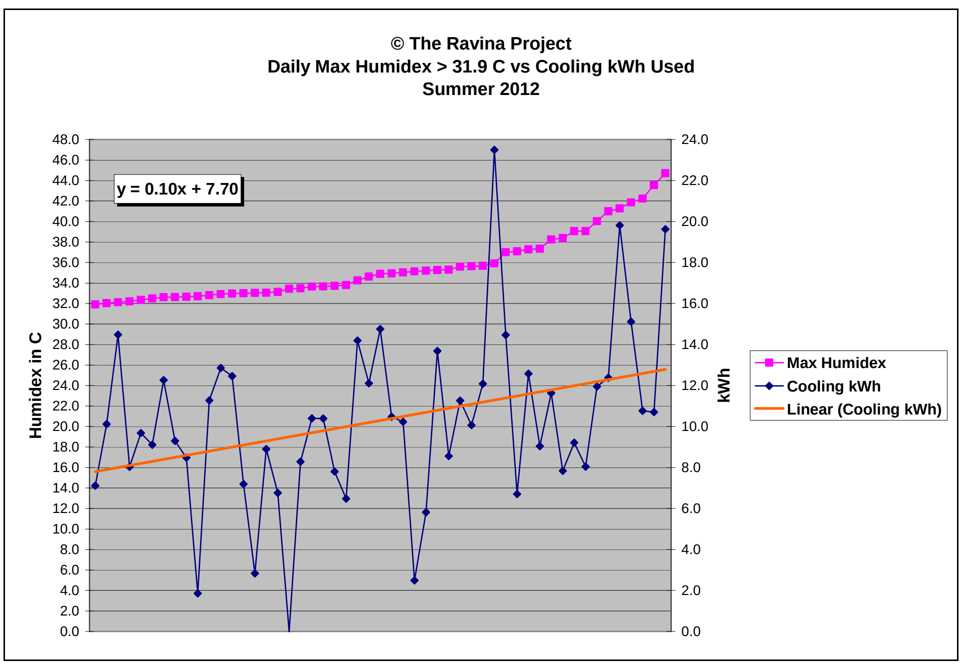


The first thing we notice on this graph is how slowly the orange line rises in response to the marginal Humidex increase. We see that the extra cooling energy used by the household is small as the daily maximum Humidex rises to 31.9 degrees C.

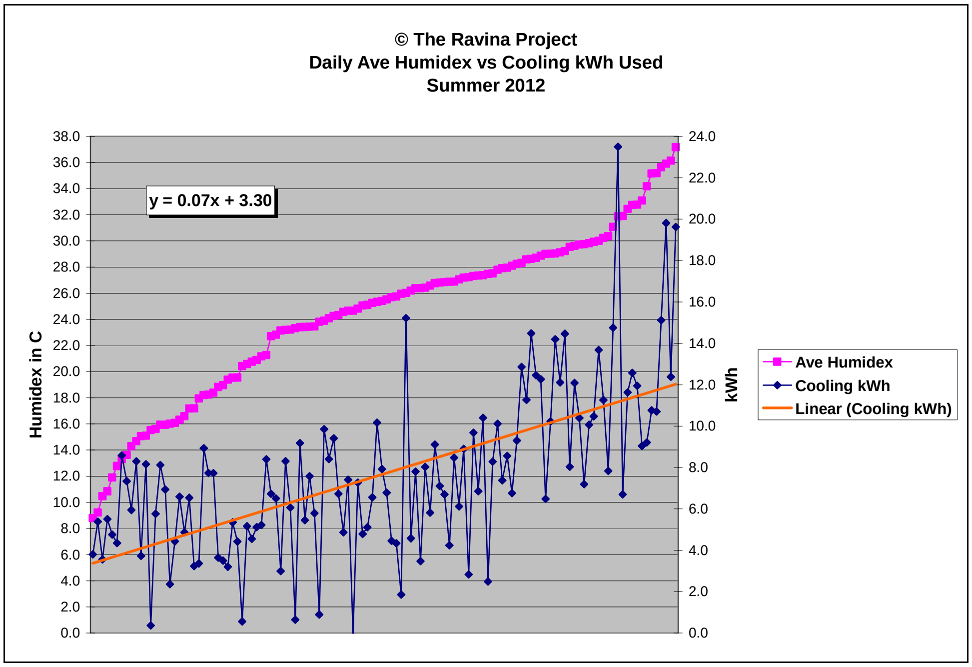
This tells us that we are less sensitive to daily maximum Humidex than heat up to a point and then the roles reverse. The roles reverse because the biggest slope increase is found below.

Consider the following graph:



Wow. The slope increases to 0.10 or ten times larger. The household's response to increased maximum daily Humidex is aggressive and in fact is the most aggressive yet. We seem to be very sensitive to maximum daily Humidex over a certain amount.

Let's consider daily average Humidex in the graph below.



Over the summer the household response is about 0.07 to average daily Humidex. Note that this response is greater by 0.01 than the maximum Humidex values. So we see the same thing here as with the temperature graphs. The night time Humidex, which is a factor in the daily average Humidex, provokes an increased marginal response from the household.

We notice in this graph, like the others, there seems to be a break point where the household energy response changes dramatically from one kind of marginal increase to a much more vigorous one.

We identified this Humidex value as 28.2 degrees C.

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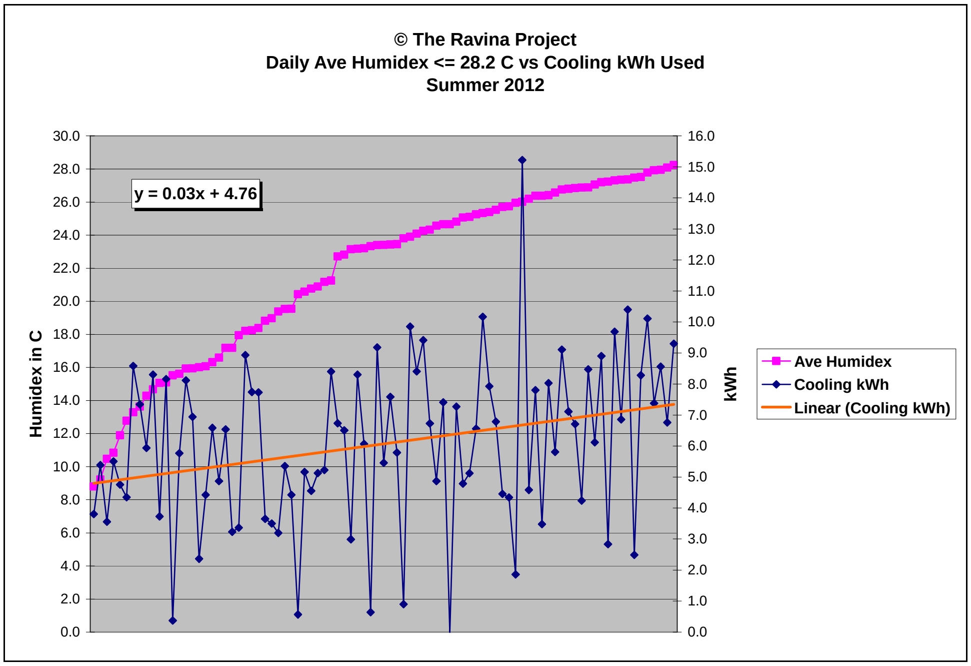
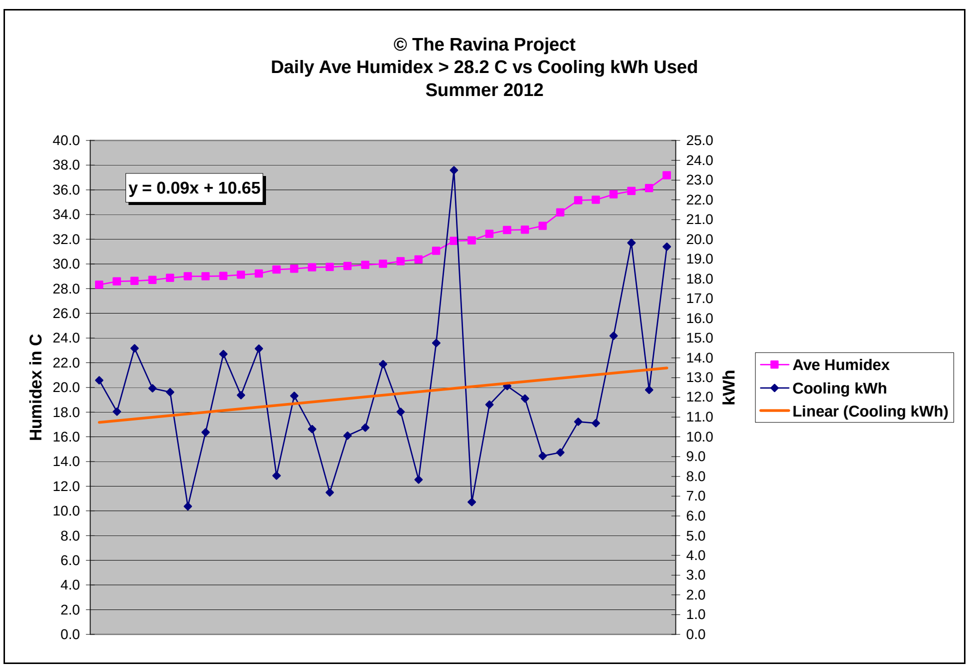
Consider the following graphs:



We see the household response as 0.03 when the daily average Humidex value is equal to or less than 28.2 C. Contrast this response to the graph above for daily maximum Humidex when the maximum Humidex is below 31.9 C. This response is three times greater and three Humidex degrees lower. We are much more sensitive to average Humidex than daily maximum Humidex by a marginal factor of three and a temperature about four Humidex degrees lower.



When the Humidex is above 28.2 C we responded by using three times more energy. The increase is not as dramatic as other categories but still significant.

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So what does this tell us?

Let's sum up in a chart with all the numbers from the graphs available.

Consider the following explanations for the chart below.

The **Transition Point in C** is the Centigrade temperature where the graphs diverge in their energy use response to increases in the variables in column one.

The **Slope Low Energy** is the household response to increases in column one below the transition point listed in column three. In each of these categories the low energy response to increases are about the same below the transition point.

The **Slope High Energy** is the household response to increases in column one above the transition point list in column three. The high energy slope is about the same for all categories just as we saw with the low energy response.

Looking closely at the graph, we see that the column values are all about the same except for the transition point. Of course this was the goal of doing this research. We wanted to determine if and how the household responds to heat and Humidity across rising heat and Humidex values.

Variable	Seasonal Slope	Transition Point in C	Low Energy Slope	High Energy Slope
Average Temp	0.07	23.2	0.02	0.10
Max Temp	0.05	27.1	0.02	0.09
Ave Humidex	0.07	28.1	0.03	0.09
Max Humidex	0.06	31.9	0.01	0.10

Bottom line, we are most sensitive to average temperature / Humidex rather than to their daily maximum relatives. Overnight values play a huge role in our energy usage. The low of 23.2 degrees C as a transition point is shocking both in its magnitude and its category, that of being daily Mean temperature. That temperature on the Fahrenheit scale is about 73 degrees, a cool daily average in many parts of the world.

One can make the argument that these data describe the sensitivity of only two people. Others may respond differently. That may be true, but we point to the different temperatures of the transition points. The distance of about 4 degrees C is huge. We concede that others may have a differential response of only 3 degrees. We argue that the absolute values could change but the relationship would remain. Bottom line the probability of the 23.2 degrees C becoming 28.5 C for other people as highly unlikely in our view.

Another argument might be made such that we are too old and our response to heat and Humidity are exaggerated. Indeed that might be the case however, there is evidence that older people feel less sensitivity to heat and cold than younger people. So we concede that there is a possibility that we respond differently than younger people. However, we fall back on the same argument … the absolute values might be different with a household made up of a different age group. We argue that the relative sensitivity among the four variables above would remain even if the absolute values do change. The general population's response to overnight temperatures and Humidex values are issues to be dealt with going further into this century.

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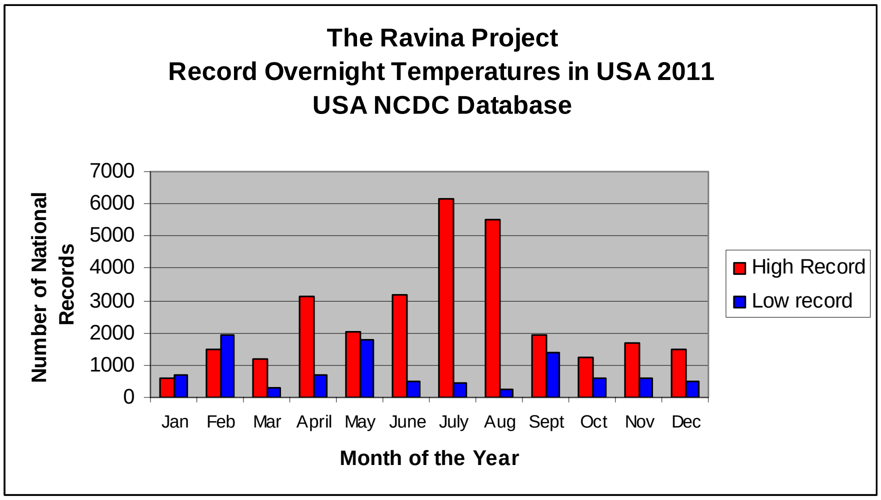
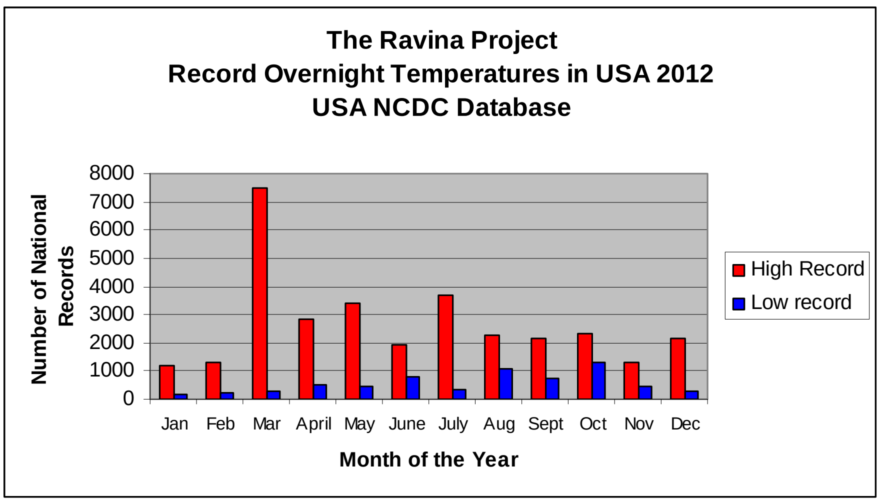
Conclusions

We want to finish the paper with some conclusions drawn from our data.

In a warming world, one of the fingerprints of CO2 pollution is the prediction that overnight temperatures will not fall as much as they would otherwise. Over the last few years in the USA thousands of record high overnight minimum temperature records were tied or broken. These records are a mixture of daily, monthly and all time records. According to U.S. National Climate Data Center's database the number of record high overnight low temperatures has increased dramatically.





These graphs make our work all the more interesting and pertinent to the issues of household cooling. Our data suggests strongly that we are more sensitive, by a substantial amount, to overnight temperatures than to maximum daytime temperatures. Global Warming will only aggravate this response meaning much more energy will be used for overnight cooling as we continue further into this century.

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Going forward

We will not be able to win the war on CO_2 without assistance at the household level with both wintertime and summertime energy efficiencies. Bottom line … we must use less energy. All techniques we can devise and test that allow us to use less energy are extremely valuable, almost like secret weapons in the brutal War on CO_2 that will dominate this century.

In a warming world city power supplies will have to account for human sensitivity to overnight temperatures. Gone are the days when equipment could cool off overnight. Night time ambient heat and people's overnight demand for cooling energy will keep the power Grid infrastructure hot as the 'summertime' expands in length. Attention to infrastructure upgrades and smart Grid rollout will be of paramount importance now and in the very near future.

Just as in the wintertime when the emphasis is on household heating efficiency through better insulation, the summertime will make efficiency demands upon the householder. We hope that some of the techniques we have outlined and demonstrated to be effective in this paper are adopted by households as new low energy ways of coping with the heat.

Our house is typical of a large proportion of the old Toronto housing stock. Our ability to calculate a range of values for our household cooling efficiency is another tool for local power Grid planners to use for summertime load planning.

Baseload power in North America is usually generated from relatively clean sources: nuclear, geothermal, hydro and the like. Peak load is generated typically from much dirtier power supplies like coal, oil and natural gas. Peak load is generally a product of daytime activity. All that is about to change as the effects of CO_2 pollution gain the upper hand in our climate. The cooling season will expand to more days; those days will be hotter for a longer time; the overnight temperatures will be greater.

Grid upgrades will be required to integrate intermittent generators like tidal, solar and wind. Some of these power supplies like solar ramp up their power very quickly as we see when our panels come out from underneath a cloud. Our 1.5 kiloWatts of PV panels go from a cloudy 350 Watts to full sun 1350 Watts in a second or two. If we were running 150 kW collectors, the cloudy 35 kW output would become 135 kW in a second or two. Or the reverse could occur … withdrawing this power from the pool of power generation in almost an instant. This spike in generation supply typically is difficult to handle by usual Grid technology. Other technologies must be in place before this kind of generation spike can be absorbed and used to power load.

Batteries use all kinds of technologies. They can be both a generator and a load at different times and can move from one mode to the other quickly. In that dual capacity then, they can load level the Grid when placed at critical locations on the Grid. If they also include intelligent electronics that reduce or eliminate other Grid killing anomalies, they will allow the creation of a Smarter Grid, resilient to many of the shocks placed upon it. The Grid will be well on its way to becoming clean power friendly.

We speculate that household energy usage data held by the local electrical utility may exhibit some of these behaviours when processed for energy responses to heat and Humidex. This project lies outside our expertise but we suggest it as a possible area of research for others given the responses we have discovered.

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"If we knew what we were doing, it would not be called research."
- A. Einstein

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NABCEP Certified Solar PV Installer™
Designer of our sun altitude compensating, solar array structure

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Appendix 1

Making a Sun Shield

We found that using sun shields kept lots of heat out of the house.

We cut a large box and laid it out flat.

We coated it with wood glue.

We pressed some foil on it shiny side up. We used the wide thick stuff made for cooking turkeys and roasts. Leave some foil extra because it will fold over to be glued onto the back.

Note we did not want to stop all sunshine from entering the house. We wanted to reflect back about 60% in each window. We have all kinds of indoor plants that require the sun. And of course the shields had to be light enough to remove quickly to enjoy afternoon and evening illumination in the house.

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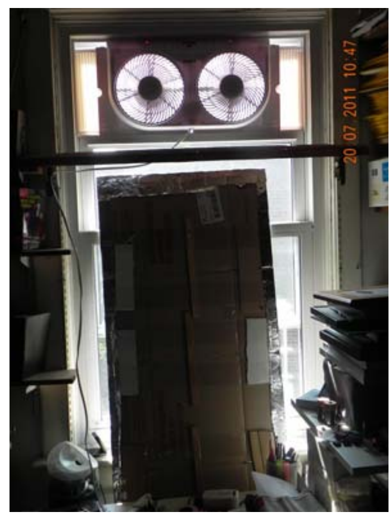
We glued some scrap wood to reinforce and stiffen the cardboard. We made a handle out of a folded over piece of duct tape … Canadian eh?

Here’s a shield being used in the upstairs office at area ‘A’ on the chimney diagram above. The exhaust fans are in operation.



The shields being used in the dining room.

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… in the plant room.

… on the back porch.

Blistering sun shine late morning with several hours to go.

You can see why shields help us out.

Must be a hot/humid day, the house is totally sealed up.

Note we take the shields down and store them in the room where they are used when they are not in use. They are light weight and just sit in the window out of reach for small children or pets. The porch door was the most difficult. Susan got a couple of magnetic hooks allowing us to hang the shield on the metal door as can be seen above.

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