Energy Performance Analysis of Ultra-Efficient Homes at Solar Decathlon 2013

by

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ABSTRACT

The objective of this thesis is to investigate the various types of energy end-uses to be expected in future high efficiency single family residences. For this purpose, this study has analyzed monitored data from 14 houses in the 2013 Solar Decathlon competition, and segregates the energy consumption patterns in various residential end-uses (such as lights, refrigerators, washing machines, ...). The analysis was not straight-forward since these homes were operated according to schedules previously determined by the contest rules. The analysis approach allowed the isolation of the comfort energy use by the Heating, Venting and Cooling (HVAC) systems.

HVAC are the biggest contributors to energy consumption during operation of a building, and therefore are a prime concern for energy performance during the building design and the operation. Both steady state and dynamic models of comfort energy use which take into account variations in indoor and outdoor temperatures, solar radiation and thermal mass of the building were explicitly considered.

Steady State Inverse Models are frequently used for thermal analysis to evaluate HVAC energy performance. These are fast, accurate, offer great flexibility for mathematical modifications and can be applied to a variety of buildings. The results are presented as a horizontal study that compares energy consumption across homes to arrive at a generic rather than unique model - to be used in future discussions in the context of ultra efficient homes.

It is suggested that similar analyses of the energy-use data that compare the performance of variety of ultra efficient technologies be conducted to provide more accurate indications of the consumption by end use for future single family residences. These can be used alongside the Residential Energy Consumption Survey (RECS) and

the Leading Indicator for Remodeling Activity (LIRA) indices to assist in planning and policy making related to residential energy sector.

DEDICATION

I dedicate this thesis to my grandmother, Swaraj Rani Garkhail (Feb 1931-Mar 2014). Among all the moment affection, one of my oldest memories of her is her telling me - to turn off the lamps when they were not needed.

ACKNOWLEDGMENTS

I take this opportunity to express my gratitude to the MSBE program professors and my thesis committee members for generously imparting wisdom and knowledge over past two years and to allow me to benefit from their tireless commitment to education.

I thank Professor Marlin Addison for accommodating all my needs and his immense perseverance in developing in me the skill set necessary for this profession.

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INTRODUCTION

1.1 Background

For over three decades, the single most globally debated subject and accepted challenge has been to plan and implement measures to mitigate climate change. Discussions have included investigation of its causation to solution strategies, both local and global, that can address the breadth of issues related to green house gas emissions - global warming, equitable distribution of resources, and above all, our dependency on carbon based fuels for the generation of energy.

Energy is our everyday necessity - in manufacturing, in buildings, in construction, in transportation, in healthcare and in farming. Response to this nebulous challenge is equally impressive in scale and multifaceted in its implementation. It demands investment, in the renewable energy sector, in creating awareness, in transparency in governance, in promoting economic fairness and inclusive policy-making, and in advancement and proliferation of cleaner and efficient technology that can manifest at the scale of everyday life.

Buildings form a vital part of the consumed energy and are therefore an inescapable part of this response strategy. The 2010 data from United States Department of Energy suggests that the building sector consumed 41% of total primary energy in the United States. Within this sector, in 2010 residential buildings accounted for 22.5% of the total energy consumption and are projected to stay around 21% for the decade.

Residential sector accounts for 32% (about $360 billion - US Census Bureau) of the total spending on construction, both new and renovation, and single-family housing has emerged as the most significant contributor. Despite the economic slump, spending on construction in the residential sector has begun recovery and recorded an increase of about 2.6% year on year in 2013.

The US Department of Energy targets 50% reduction in energy consumption in residences by 2030. In pursuit of this vision, the international collegiate competition 'Solar Decathlon' [source: www.solardecathlon.gov] brings together - affordability, innovation and efficiency in building construction and operation, and most importantly, solar based technologies for energy conservation and generation - to the residential sector by means of workable houses. These are ultra-efficient homes.

1.2 Ultra-High Efficiency Homes and view of the Solar Decathlon

The US Department of Energy DOE describes ultra-efficient home design as whole building design approach that combines emerging technologies in energy-efficient construction, lighting, household appliances and renewable energy systems for water heating and electricity. [source: www.energy.gov] Such a design takes advantage of the local climate and site conditions to incorporate pasive solar architecture and techniques for space heating or cooling and promotes energy - efficient landscaping strategies.

The primary intent of an ultra efficient home as defined by DOE is to reduce home energy use as cost-effectively as possible, and then meet the reduced requirements by means of renewable energy systems.

The US Department of Energy organizes Solar Decathlon as a biennially held international competition that challenges 20 collegiate teams to design, build and operate an attractive, affordable and highly energy efficient - solar powered home. [source: www.energy.gov]

Since its inception in 2002, the competition houses have regularly showcased improvisations of existing technologies and products available in the market and/or prototypes of technology that are still under development. Traditionally, these technologies range from a building material with higher thermal performance, eco-friendly products, mechanical equipment/ controlling systems that enhances the efficiency of the comfort system, products for increasing efficiency in energy generation by the solar panels, products for water conservation, products for more efficient lighting, and in general, ideas that enhance lifestyle and overall increase energy-use efficiency in the building.

The open competition allows visitors, business owners and enthusiasts to tour these homes; see the technologies in action and to gather ideas to install some of these in their own communities and homes. The Solar Decathlon has a global presence; similar events like *Solar Decathlon Europe* and *Solar Decathlon China* serve as extended regional initiatives.

The ideas for developing ultra-high efficiency homes and using solar related technology for energizing the home and for comfort systems has been around for over seven decades. Most notable of these are the Massachusetts Institute of Technology (MIT) Solar houses.

Solar - 1 - featured as the US Department of Building technology as a milestone building of the 20th century was the first of the prototype solar houses developed by MIT in 1939 to use solar heating during winter and also perform experiments for summer cooling. MIT continued this program to develop a series of prototype solar houses that tested various technologies -ranging from solar heating, cooling, thermal storage and phase change materials.

A pioneer in solar driven architecture and technology, Dr. Maria Telkes, in 1945 at the Dover house (figure 1), was already experimenting with materials and technology to introduce chemicals that effectively store solar thermal energy to be used in congruence with comfort systems.

Figure 1: Dr. Maria Telkes and Eleanor Raymond at the Dover House, MA (1945).

Technology driven intervention was not the only approach, *Passive Architecture* techniques have also been equally necessary in evolution of the design of solar based architecture. A prime example is the Rosenberg residence in Tucson, Arizona,(figure 2) where architect Arthur Thomas Brown in 1946 use combination of south facing glass and inward facing walls that were painted black (figure 3) to effectively store and distribute heat from solar radiation.

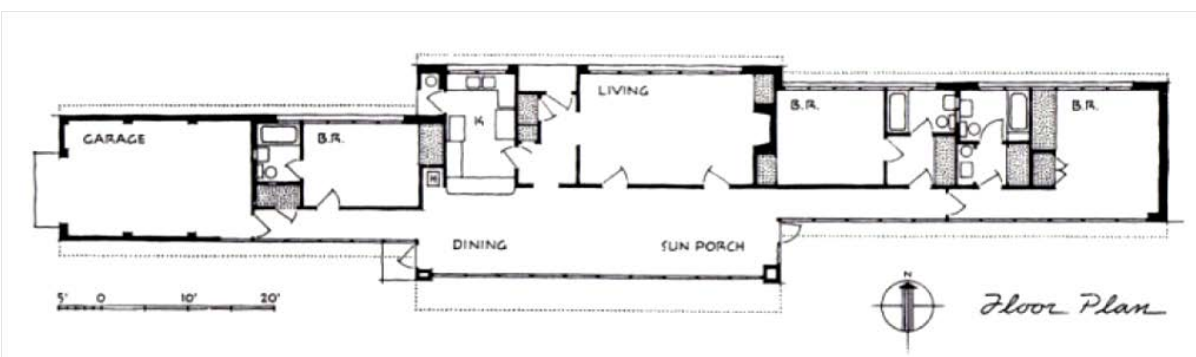


Figure 2: Plan of the Rosenberg residence with expansive south glass.

Many of the fundamental ideas underlying the solar houses in the Solar Decathlon to date use the principles established by such pioneers in the last century. The notion of making a solar powered energy efficient house is not a novelty but rather a continuation of a deep rooted tradition to discover greater efficiency in the technologies associated with harnessing the solar power, to enhance functionality and flexibility of the spaces we dwell in and to be able to rapidly evolve along the technology driven lifestyle.

Figure 3: Internal faces of corridor walls painted black to re-radiate the solar gains. Rosenberg Residence, Tucson, Arizona.

1.3 Energy-use in residential sector a case for single family house

The Energy Information Administration EIA defines Single Family Housing Unit as a housing unit, detached or attached, that provides living space for one household or family. Attached houses are considered single-family houses as long as they are not divided into more than one housing unit and they have an independent outside entrance. A single-family house is contained within walls extending from the basement (or the ground floor, if there is no basement) to the roof. A mobile home with one or more rooms added is classified as a single-family home. Townhouses, row-houses, and duplexes are considered single-family attached housing units, as long as there is no household living above another one within the walls extending from the basement to the roof to separate the units. The EIA also defines Site Energy as the Btu value of energy at the point it enters the home, sometimes referred to as "delivered" energy. The site value of energy is used for all fuels, including electricity.

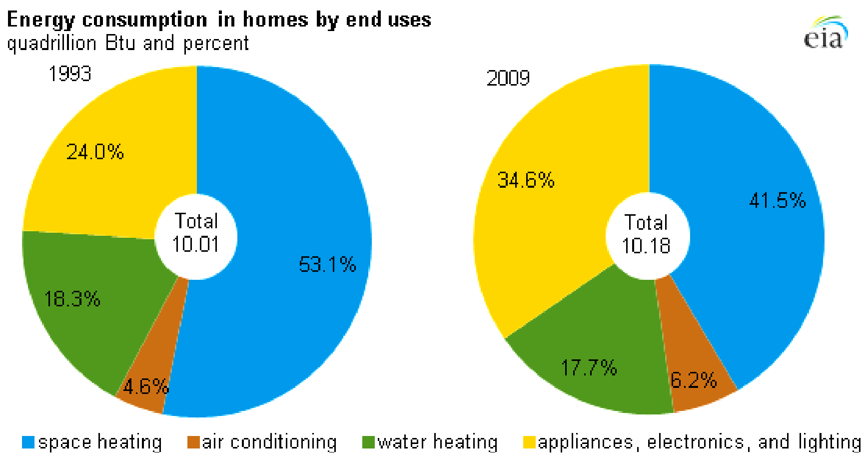


Figure 4: Energy consumption in homes by End - Use. Source: U.S. Energy Information Administration, Residential Energy Consumption Survey (2009).

The data from the 2009 Residential Energy Consumption Survey (RECS) on Single family houses suggests that there are nearly 80 million single family residences in United States that consume nearly 8 quadrillion Btu energy annually. This accounts for nearly 23 % of the total energy consumption in USA.

RECS data (table 1) sample size consisted of 19,000 surveyed houses across America in various counties across the climate zones and has a verified reporting accuracy of 79% for the population. A statistic derived from this data for houses less than 2000 sq ft (60% total sample size) suggests that they consume a total of 4.8 quads Btu of energy at an average μ of 70 million Btu per household. (Equation 1)

Housing Unit Characteristics and Energy Usage Indicators	**Total Housing Units**[1] (millions)	**Site Energy Consumption**[2]			
		Total (quadrillion Btu)	**Per Household** (million Btu)	**Per Household Member** (million Btu)	**Per Square Foot** (thousand Btu)
Total U.S	113.6	10.183	89.6	34.9	45.5
Housing Unit Type					
Single-Family	78.6	8.142	103.6	37.7	42.8
Single-Family Detached	71.8	7.595	105.7	38.0	42.6
Single-Family Attached	6.7	0.546	81.3	33.0	46.0
Year of Construction					
Before 1940	14.4	1.590	110.1	45.5	51.6
1940 to 1949	5.2	0.502	96.7	36.4	52.0
1950 to 1959	13.5	1.315	97.1	38.1	52.5
1960 to 1969	13.3	1.167	87.9	35.8	50.2
1970 to 1979	18.3	1.445	79.0	31.2	46.9
1980 to 1989	17.0	1.306	77.0	30.7	43.5
1990 to 1999	16.4	1.435	87.8	33.0	39.9
2000 to 2009	15.6	1.423	91.5	32.4	37.1
Total Square Footage[6]					
Fewer than 500	2.8	0.118	41.6	27.9	108.9
500 to 999	24.8	1.362	54.9	26.6	71.0
1,000 to 1,499	24.1	1.748	72.5	27.8	58.6
1,500 to 1,999	18.4	1.653	89.8	33.7	51.6

Table 1: Extracted from [RECS DATA] Average Site -energy consumed by Single-Family Homes, 2009. (Complete table in Appendix B)

Based on the data collected by RECS (table 1), for American residences with area ≤ 2000 sq ft the national average annual consumption of site energy can be calculated as -

$$\mu_{\frac{EN.CONS}{H.HOLD<2000\ sq\ ft}} = \frac{\sum(E_k * A_k)_n}{\sum A_n} \cong 70\ mill\ BTU \quad -(Eq.1)$$

Since the site energy includes various fuel types used across the states it is necessary to distinguish the electrical component of that energy use.

Housing Unit Characteristics and Energy Usage Indicators	Total Housing Units[1] (millions)	Average Site Consumption (million Btu per household using the fuel)					
		Total[2]	Electricity	Natural Gas	Propane/ LPG	Fuel Oil	Kerosene
Housing Unit Type							
Single-Family	78.6	103.6	43.7	75.5	45.9	85.1	10.8
Single-Family Detached	71.8	105.7	44.9	76.8	46.0	85.6	10.4
Single-Family Attached	6.7	81.3	30.8	63.2	38.6	78.8	Q
Total Square Footage[6]							
Fewer than 500	2.8	41.6	16.1	35.9	16.0	47.4	Q
500 to 999	24.8	54.9	25.7	43.5	28.4	49.4	21.9
1,000 to 1,499	24.1	72.5	35.6	56.4	29.0	62.7	14.9
1,500 to 1,999	18.4	89.8	41.5	67.1	43.5	62.8	13.9

Table 2: Extracted from [RECS DATA] Average Consumption Site Energy by Fuel Type, 2009. (Complete table in Appendix B)

A breakdown of the average annual site energy in single family residence by fuel type as produced in survey data by the Energy Information Administration for 2009 (table 2) reported that on an average the electricity component accounts for the of the site energy can be calculated

$$percent\ \mu_{el} = \frac{\sum\{\frac{e_k}{E_k} * (T.H\ Unit)_k\}_n}{\sum (T.H\ Unit)_n} * 100 = (46 - 48)\% \quad (Eq.2)$$

Based on the available data and using the above two equations we can conclude that on an average the Single Family Residences with areas (500 - 2000 sq ft) may consume between 32.2 - 33.6 million BTU (9437 - 9847 KWh) of electrical energy annually. Furthermore, the national average for price of 1KWh = $ 0. 12. This means that on average the electric bill for the typical single family residence with area less than 2000 sq ft ranges between $ 1100 - 1200 annually.

Finally, to put these numbers into a life-cycle context - the RS Means costs data from 2013 [source: http://rsmeans.reedconstructiondata.com] shows that the average life cycle for major residential components like roof and walls is between 20-30 years, lifespan for the mechanical systems is estimated to be between 10-15 years and for the appliances the average lifecycle is between 8-14 years but reducing.

Reflecting back on the RECS data to the year of construction, at any point in the next 30 years we should expect a stock of nearly 15 million housing units requiring some form major retrofit and nearly 20-25 million houses looking to upgrade appliances.

This means that at any given time in the future 30 years, prior to hitting another 5-10 year slump, there will be continuous demand for upgrades in the single family residence, and can be translated as an opportunity to explore better construction materials and more efficient appliances - and perhaps as an opportunity to make the single family residence with area less than 2000 sq ft a model for the Ultra-High Efficiency Home.

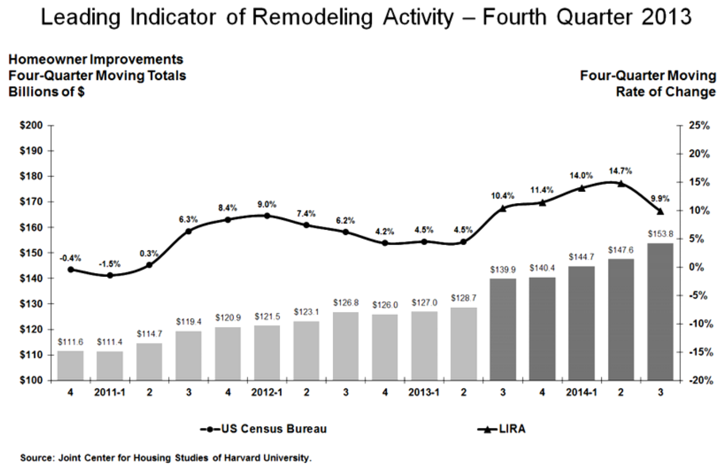


Figure 5: Leading Indicator for Remodeling Activity LIRA on average there is annual growth recorded between 3-4%.

CHAPTER 2

OBJECTIVE AND SCOPE

2.1 Objective of the Thesis

Prior to outlining the objective and the scope it is important to mention and define the following two terms - "Energy Performance" and "Energy Conservation Measure - ECM"

1. ASHRAE - 105 /2014 - [https://www.ashrae.org] defines "Energy Performance" as an expression of energy use relative to specific building characteristics or other factors that allows potential comparison with other proposed buildings, new buildings, or existing buildings.
2. A DOE endorsed energy end-use related definition of the term -Energy conservation measure (ECM) that is more consistent with low rise residences is - a building material or component whose use will affect the energy consumed for space heating, space cooling, domestic hot water or refrigeration."

The main objective of this research is to (i) segregate energy use by equipment type, and (ii) analyze the performance of heating and cooling systems exhibited in the Solar Decathlon 2013 houses through a comparison of post-construction actual energy consumption data.

A subsequent objective is to use this comparison to identify specifics of those ultra - efficient building characteristics from an energy performance standpoint that can be considered t be future ECMs, and can perhaps serve as indicators to forecast future trends in this class of buildings.

2.2 Scope of the Thesis

The scope of this thesis for the first part is to use a spreadsheet program as a platform to perform analysis using statistical tools to segregate energy use data and associate the energy signatures with the end-use. This evaluation leads to the main objective and the second part where the scope of the thesis will be to extend this platform to perform thermal analysis using statistical tools and inverse modeling methods. The methods identified are - Steady state model, Time Series Analysis and thermal networks as a partial attempt to explore the larger ECM related research as outlined in 2.3.

The Energy-consumption data collected for prototype homes during the competition period October 3, 2013 to October 11, 2013 has been used for the research. The collected data is a 15 min interval record of energy use and requires quality check. Other parameters measured and recorded are temperature, humidity and solar radiation. Humidity and solar radiation data have not been included in this study. All 14 prototypes had more than adequate shading from direct solar radiation for solar gain to have a large impact.

2.3 Larger scope of related research and HUD - suggestions.

The US Department of Housing and Urban Development (HUD) maintains a publically available record of suggested ECMs and good operational practices for assistance to housing authorities and homeowners to improve their home energy performance in a cost effective method.

Following are some the common residential ECMs recommended by the HUD as being fundamental to an energy efficient residential building and must be considered as a precursor to the Ultra-High efficiency houses.

1. Building Envelope [B] - The primary intent with envelope related ECMs is to improve energy performance and mitigate losses due to the building envelope (Walls, roof, window doors etc). These usually require optimization (increase or decrease) insulation - strategizing thermal performance of exterior skin, increase or decrease thermal mass/ structure. ECMs with emphasis on windows and doors can be related to shading, increased day lighting control, installing better performance glass, better seals to avoid infiltration or leakage losses.
2. Space Heating and Cooling [H] **-** The emphasis with heating and cooling ECMs is to improve the efficiencies of the primary and the secondary mechanical systems, a few common residential ECMs entail installing and repair of vent dampers for better flue discharge, switching to electric ignition instead of pilot flame in boilers, sealing and insulating ducts and pipes to minimize losses, better heat exchangers and better performing radiators controls, installing geothermal heat-pumps etc. Better control systems and programmable thermostats have become popular as a low investment high return ECM.
3. Domestic Water Heating System [W] - The domestic hot water heating and supply accounts for nearly 10% of the energy use in the typical residence, some of the most effective ECMs for water heating are installing water-efficient showerheads and faucet aerators, insulating Hot Water tanks, installing Hot Water Off -peak controls, switching laundry to cold rinse, installing better water heaters - there are hybrid water heating technology available that can increase savings from heat recovery and combine with the heat pump, installing solar water heating system whenever possible.

4. Lighting [L] - Perhaps the quickest and most cost effective ECMs are related to lighting, switching from Incandescent to CFL lamps or LED lamps if possible, installing task based lights, and better lighting controls for interior and exterior, changing habits to maximize use of day lighting whenever possible.
5. Miscellaneous/ Appliance based ECMs [M] - When changing to a newer appliance, opting for an energy star rated or equally efficient appliances, especially the refrigerators and washer/ dryers. Installing check meters or individual meters, opting for high efficiency pumps with larger bladder tanks to minimize frequent pump-cycling.

This is a very large field and each of these ECM segments by themselves requires detailed exploration. For this thesis the emphasis is on energy use data of ECMs related to *Space heating and Cooling [H]* and will therefore direct the focus of and scope of the thesis during the second part of this analysis.

CHAPTER 3

LITERATURE REVIEW

3.1 Measurement and the Simulation Approaches

The real motivation for a robust approach for energy performance evaluation took shape as a response to the 1973 middle-east oil embargo against USA and its allies and caused an escalation in efforts to reduce energy consumption. The orthodox rule of thumb based estimation techniques prevalent at the time were grossly inaccurate, and there was a drive to develop scientific and computational methods that could estimate energy use with greater accuracy and that could utilize a larger set of parameters namely the dynamic heating and cooling loads.

Leveraging from similar research and testing done in 1960 for fallout shelters, physics based equations were developed that could be sequenced into an algorithm to predict energy performance, further these were refined and proofed against actual measured data to develop the quasi-steady state models for the primary and secondary HVAC equipment. This clearly was the beginning of building energy simulation approach for energy performance evaluation. The two approaches to energy performance evaluation of ECMs have a common goal and share the same scientific premise but have different and complimentary working methodologies.

Prior to discussing the two approaches any further it is necessary to define the following terms -

1. ASHRAE 90.1 2010 defines the "Baseline Building Design" as a computer representation of a hypothetical design based on the proposed building project. The representation is used as the basis for calculating the baseline building performance for rating above-standard building design.

2. ASHRAE 90.1 2010 defines the "Baseline Building Performance" as the annual energy cost for a building design intended for use as a baseline for rating above-standard design.

First, the measurement based approach relies analysis on the before and after energy use data collected from either utility bills or measured as daily/ hourly energy use or energy use from isolated components to determine the effectiveness of an ECM. Next to evaluate savings relative to the baseline building performance attributed to the post ECM in the buildings.

Second, the simulation approach relies on creating a baseline building design by modeling the HVAC equipment and all possible thermal parameters of the building to evaluate the energy performance of this building as a hypothetical performance model. This model can be calibrated with actual energy use to establish the baseline building performance and used to evaluate the benefits from proposed ECMs.

The nature of this research, availability of an energy use interval data, and lack of detailed knowledge of the building envelope (walls, roof, and windows) and other thermal parameters for all the prototypes inform the decision on measurement based method for thermal analysis of building.

3.2 Thermal Analysis Methods - Steady State or Dynamic

Calculation for annual savings through reduced energy consumption during operation of the building requires understanding of instantaneous consumption during the heating or cooling seasons which is simply the product of the instantaneous loads on the building and the reciprocal of the efficiency of the HVAC equipment. The two distinct methods for this based on complexity of project and the level of detail expected form the calculations are the Steady State Method and the Dynamic Method.

A Steady State Method commonly referred to as the Bin method due to degree day bins and temperature bins akin to the *probability mass function* in mathematics. The data is typically expressed as histograms and required variable values are a discrete set.
A Dynamic Method based on transfer function also account for the transient effect of the thermal mass and time constants and are therefore fundamentally akin to the *probability density function* in mathematics. The data is typically expressed as line or exponential continuous graph and the variables belong to a continuous set.
ASHRAE Handbook of Fundamentals in 2013 classifies the various methods for thermal analysis of buildings for the purpose to evaluate the building energy performance.
This classification is based on method of analysis - steady-state or dynamic, based on regression, bin methods, transfer function, simulation or thermal networks etc. and on the technique as forward, inverse or hybrid; and it also takes into account the processing of variables involved like Time (t), Temp (T), Humidity (H), Solar (S), Wind (W) and Thermal Mass (TM) to determine accuracy and applicability of these methods for a specific building situation. (Refer Appendix A.2 and A.3 for details of Classification of Methods of Thermal Analysis of Buildings)

3.3 Forward modeling

ASHRAE describes a forward model as a computer aided thermodynamic model of a building created using complete mathematical description of all significant components of the building including envelope, systems, geometry, insulation properties, occupancy, geographical location, operations schedule etc. such that all these parameters can be computed using fundamental engineering principles to derive a hypothetical annual energy use pattern for the modeled building.

Traditionally these models have been used during the design stages to size HVAC systems and simulate the performance of the proposed building design for new construction, hence the term 'forward' but increasingly the simulations are being used to model existing buildings, an approach referred to as calibrated simulation to explore potential operations savings, predict maintenance issues and support decisions for any future retrofits.

While the ASHRAE description focuses on the energy performance from a thermal standpoint, a wider more general extrapolation of the method already common in industry is as follows - A forward modeling method involves creation of a virtual model that is based on the concerned engineering principles and incorporates maximum possible and relevant variables to predict the hypothetical performance of the components of that virtual model.

Forward modeling is as relevant as the whole building approach and can also be done piecemeal for specific components like PV Sizing and performance, appliance performance based on schedules, calculations for insulation etc.

The illustrations that follow are two examples of simulations prepared during the design stage for the SHADE house that can be considered as forward models.

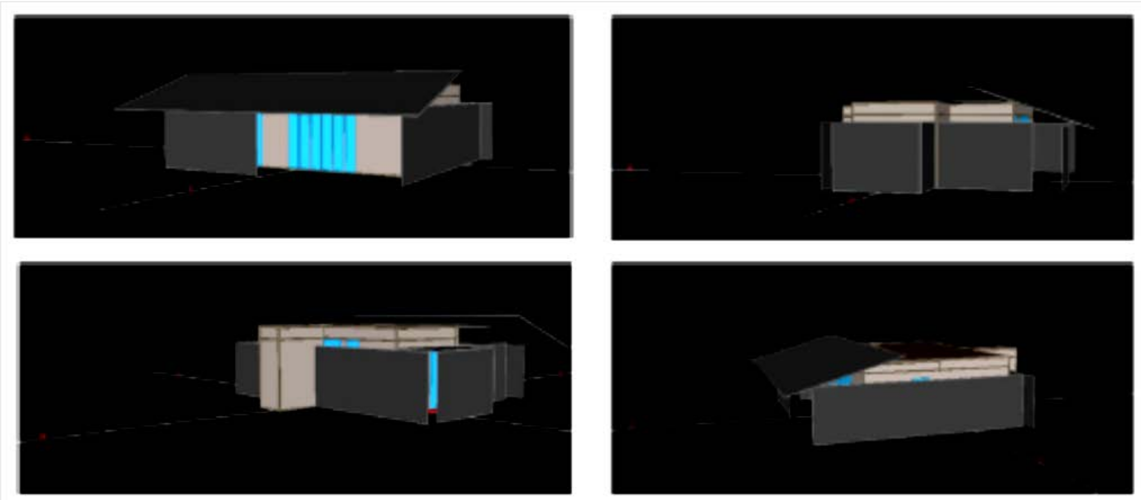


Figure 6: eQUEST model for the envelope and shade screens for the SHADE house.

As expected the eQUEST model revealed the largest contributor to the solar heat gain in the SHADE home to be the Bi-Fold Door on the south facing wall at the patio. The second largest contributor to the solar heat gain is the roof. (Refer to Appendix A.4 for related Insulation study and Cooling load calculations)

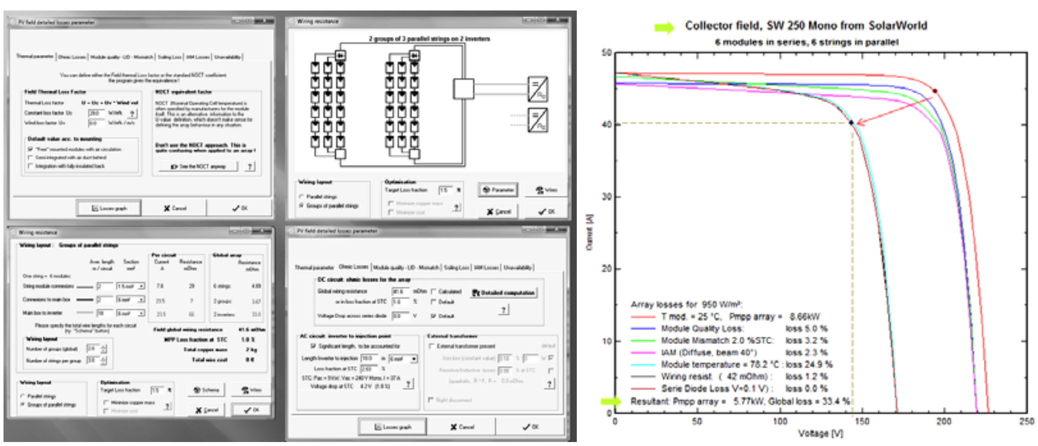


Figure 7: Simulation, PV Sizing and Component adaptability with PV Syst V6.0 [Study part of ATE- 598]

3.4 Inverse modeling

If the forward method uses engineering equations and fundamental laws of physics to forecast performance based on the modeled building parameters in the hypothetical model then by contrast the inverse theory - inverse models - do the opposite. An inverse model is used to simply reverse calculate those parameters that influence the energy performance from given data of an existing operational building. This is also referred to as the inverse problem and is actually part of a very large subject in applied mathematics and economics known as *System Identification*.

As described by Subbaroa in 1988 [Ref. Heating and Cooling of Buildings Kreider], an inverse model is both faster and accurate when compared to forward model during its processing, but cautions about keeping the number of adjustable parameters low due to the not so rich data content and the repetitive conditions in which it is collected and a high possibility of error accumulation.

Steady-State Inverse Models - described in its simplest form of an inverse model, it essentially tracks the behavior of energy consumption as a function of outdoor conditions. This model as explained by Curtiss [Ref. HVAC Handbook] can be calculated by statistically regressing monthly utility consumption data against average billing period temperatures. These models can be made more accurate with use of change-point regression procedures that simultaneously solve for several parameters including a weather independent base-level parameter, one or more weather dependent parameters, and the point or points at which the model switches from weather dependent to weather independent behavior. One popular variant and one of the earliest methods is the Princeton scorekeeping method - PRISM developed by Fels and the also referred to as the ASHRAE Variable Degree Day. [Ref Energy Management Handbook] [Ref. Kreider 2010]

The simple steady state inverse model can be explained as:

C_{base} = Base level (energy other than heating or cooling) [Btu/yr]

$$\beta = \frac{K_{tot}}{\eta} = ratio\ of\ total\ heat\ loss\ coefficent\ and$$
$$the\ efficiencyof\ the\ HVAC\ system\ [Btu/(h * °\mathrm{F})\ ]$$

$T_{bal} = balance\ point\ temprature$ °F

These are parameters that are assumed constant throughout the year.

The parameters are determined by minimizing the sum over all period 'i' of squared deviations between data and the model.

$$C_i = \frac{C_{base} * n_i}{365} + \beta * D_{h,i}(T_{bal})$$

And

$$C_{yr} = C_{base} + \beta * D_{h,yr}(T_{bal})$$

The model obtained by regression is considered satisfactory if the R^2 is above 0.8 and the standard error for C_{yr} is small. If the values do not comply with these criteria, another model should be identified.

In general, in system identification, a dependent variable for regression may have a small standard error while the parameters of the model remain uncertain with higher standard errors.

Thermal networks are forms of Dynamic models with the simplest case being the RC network. Here the entire building mass is lumped as its thermal capacity into a singular massive node. Although unrefined, this model is a great tool to understand the time constant or thermal lag for the building.

The regression equations for the thermal network model can be derived while assuming the following:

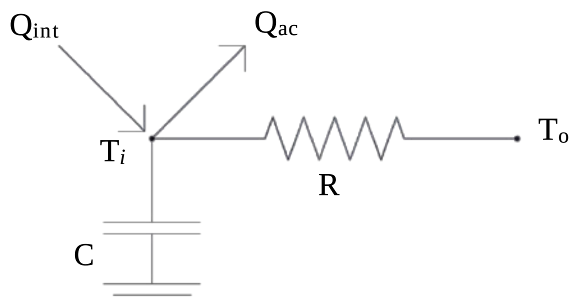


Figure 8: Single Node Thermal Network

$$C\dot{T}_i = \left(\frac{T_o - T_i}{R}\right) \pm \dot{Q}$$

C = Capacitance, R = Resistance, T_o= Outside air Temperature
T_i = Internal Temperature, Q_{ac} = Work done by AC to remove heat
Q_{int} = Heat Gain

The drawback of the RC Network is that it is does not account for difference in zones and surface temperatures of those zones. It treats the entire building mass as a single capacitor and therefore any error in the judgment of this C (Capacitance) will result in grossly inaccurate results. However modifications to this set up with a dynamic C value can be done using method of Jones (1983) - not in scope of this study.

3.5 Processing of Data

Descriptive statistics consists of methods for organizing and summarizing information. Inferential statistics consists of methods for drawing and measuring the reliability of conclusions about a population based on the sample of the population. [Ref. Statistics - Neil A. Weiss]

3.5.1 Sampling

A set of data or collection of values under consideration of a statistical study is termed as a population set. A *sample* is that part of the population from which information can be obtained. There are numerous sampling procedures defined in statistical analysis for the purpose of design of an experiment, for example the simple random sample, a systematic random sample, cluster sample, stratified sampling and multi stage sampling.

1. A *cluster sampling* requires dividing the population into groups and obtaining simple random samples of the cluster or using all the members of the cluster population.
2. A *stratified sampling* process requires division of the population set in sub populations called *strata*, and then sampling may be done from each *stratum* or the entire sub population set may be used if the data set is not very large, provided that the members of stratum i.e., the values are homogenous relative to the characteristic under consideration.

For the purpose of our research, a sequential combination of cluster sampling and stratified sampling has been invoked. In statistics such a process is called a *Multi-stage sampling*. [RECS use s a variant of this approach at a much larger scale]

3.5.2 Principles of Experimental Design

As explained by Weiss, in a designed experiment, the items on which the experiment is performed are termed as experimental units.

Following are the principles of experimental design that enable the researcher to conclude that the differences in results are not attributed to chance and are likely caused by the treatment.

1. *Control*: two or more treatments can be compared.
2. *Randomization*: the experimental units should be randomly divided into groups to avoid unintentional selection bias.

3. *Replication*: a sufficient number of experimental units should be used to ensure that randomization creates groups that resemble each other closely.

The following terminology can be simplified as follows:

1. *Response Variable*: is the characteristic of the experimental outcome that is to be measured or observed.
2. *Factor*: a variable whose effect on the response variable is of interest in the experiment.
3. *Levels*: the possible values of a factor.

3.5.3 Measures of center and Measures of Variation

This is a well known subject and can be found in most statistics text books. Therefore I will not get into any detailed definition but just briefly mention that the widely accepted measures of center are the mean (average), the median (middle observation), and the mode (greatest frequency).

Measures of Variation are the range (Max - Min value), sample variance (averaged squared deviations from the mean) the standard deviation (square root of sample variance).

NOTE 1: The sample set of the 14 prototypes were designed for different climate zones and tested in Irvine, CA. The collected data is used during the study and are statistic standard deviations σ and the population means μ.

NOTE 2: During the process of sorting and cleaning of data (discussed in methodology) there was a need for ease of handling the large data set and and easier recognition and rejection of possible outliers - *standardization of the variables* was done using the *z- scores*.

3.5.4 Regression, Coefficient of Determination and Correlation

This too is a commonly available knowledge therefore I will only briefly mention the subject to emphasize its importance and the fundamental role to the analysis part of the research.

1. The *Least - Square Criterion* is that the line that best fits a set of data points is the one having the smallest possible sum of squared errors.
2. *Regression Line* is the line that best fits a set of data points according to the least square criterion.
3. *Regression Equation* is the equation of the regression line and for a set of *n* data points is $\hat{y} = b_0 + b_1 x$, where $b_1 = \frac{S_{xy}}{S_{xx}}$; $b_0 = \bar{y} - b_1 \bar{x}$.

The notation used in regression and correlation - for a set of *n* data points, the defining and computing formulas for S_{xx} , S_{xy} and S_{yy} are:

Quantity	Defining Formula	Computing Formula
S_{xx}	$\sum (x_i - \bar{x})^2$	$\sum x_i^2 - \frac{(\sum x_i)^2}{n}$
S_{xy}	$\sum (x_i - \bar{x}) * (y_i - \bar{y})$	$\sum x_i y_i - \frac{(\sum x_i) * (\sum y_i)}{n}$
S_{yy}	$\sum (y_i - \bar{y})^2$	$\sum y_i^2 - \frac{(\sum y_i)^2}{n}$

4. Visual criterion for rejecting a regression line - if the data points in a scatterplot do not appear to be scattered about a line.
5. How valuable is a forecast or prediction based on a certain regression line?
   In order to predict the utility of a regression line we evaluate the percentage of variation in the response variable attributed to the predictor variable. To do this

we need to find a) the total variation in the response variable and b) the variation observed in the values of the response variable that is explained by the regression.

6. To measure the total variation in the observed values of the response variable we need the sum of squared deviations of the observed values of the response variable from the mean of those values. This is called *Total Sum of Squares* **SST.**

   Thus $\boldsymbol{SST} = \sum(y_{\boldsymbol{i}} - \bar{y})^{\mathbf{2}}$

7. To amount of variation in the observed values of a response variable that is explained by the regression is SSR and is the sum of squares of all differences between the total variation in that observed value $(y_{\boldsymbol{i}})$ from the mean $(\bar{y})$ and the variation between the predicted values $(\hat{y}_i)$ from the observed value $(y_{\boldsymbol{i}})$ of that response variable.

   Thus $\boldsymbol{SSR} = \sum(y_{\boldsymbol{i}} - \bar{y})^{\mathbf{2}}$

8. *Coefficient of Determination*, r^2 is the proportion of variation in the observed values of the response variable explained by the regression.

   Thus $\boldsymbol{r^2} = \boldsymbol{SSR/SST}$

9. Correlation is or linear correlation coefficient *(r)* reflects the slope of the scatterplot and describes the relation between the response and the predictor variables - a |r| closer to 1 (magnitude) means a strong relation and the +ve or -ve signs suggest the upward or downward trend of the response variable.

$$r = \frac{\frac{1}{n+1}\sum(x_i - \bar{x})(y_i - \bar{y})}{S_x S_y}$$

3.5.5 Hypothesis Test

To draw any substantial inference from the data there are two types of hypotheses tests used. First, a one mean Z - test was performed with assumption that the derived σ from the data is accurate. Second, a Non-pooled T test is performed to determine the averages of two populations of energy use data during idle stages during the idling stage ad during the active stage.

3.5.6 The Regression Model and Analysis of the Residuals

A reasonably acceptable regression model can be used to forecast the possible values in the response variable given a certain predictor variable. The following assumptions for regression model for the purpose of inference are made.

1. Equal conditional standard deviations for the response variable are same for all values of the predictor variable.
2. For each value of the predictor variable x (temp) the conditional mean for the response variable y (energy use) is derived from the equation of the form $\beta_0 + \beta_1 x$

[Ref. Calculus and its Applications, Marvin L Bittinger]

The Analysis of residual (e_i) is done to decide whether we can reasonably presume that the assumptions for the regression inference are met, and if the inferences can be reasonably accepted and is expressed as a standard error of the estimate S_e.

$$Residual\ e_i = y_i - \hat{y}_i$$

$$S_e = \sqrt{\frac{SSE}{n-2}} = \sqrt{\frac{\sum(y_i - \hat{y}_i)^2}{n-2}} = \sqrt{\frac{\sum e_i^2}{n-2}}$$

CHAPTER 4

METHODOLOGY

4.1 Process Flow-chart

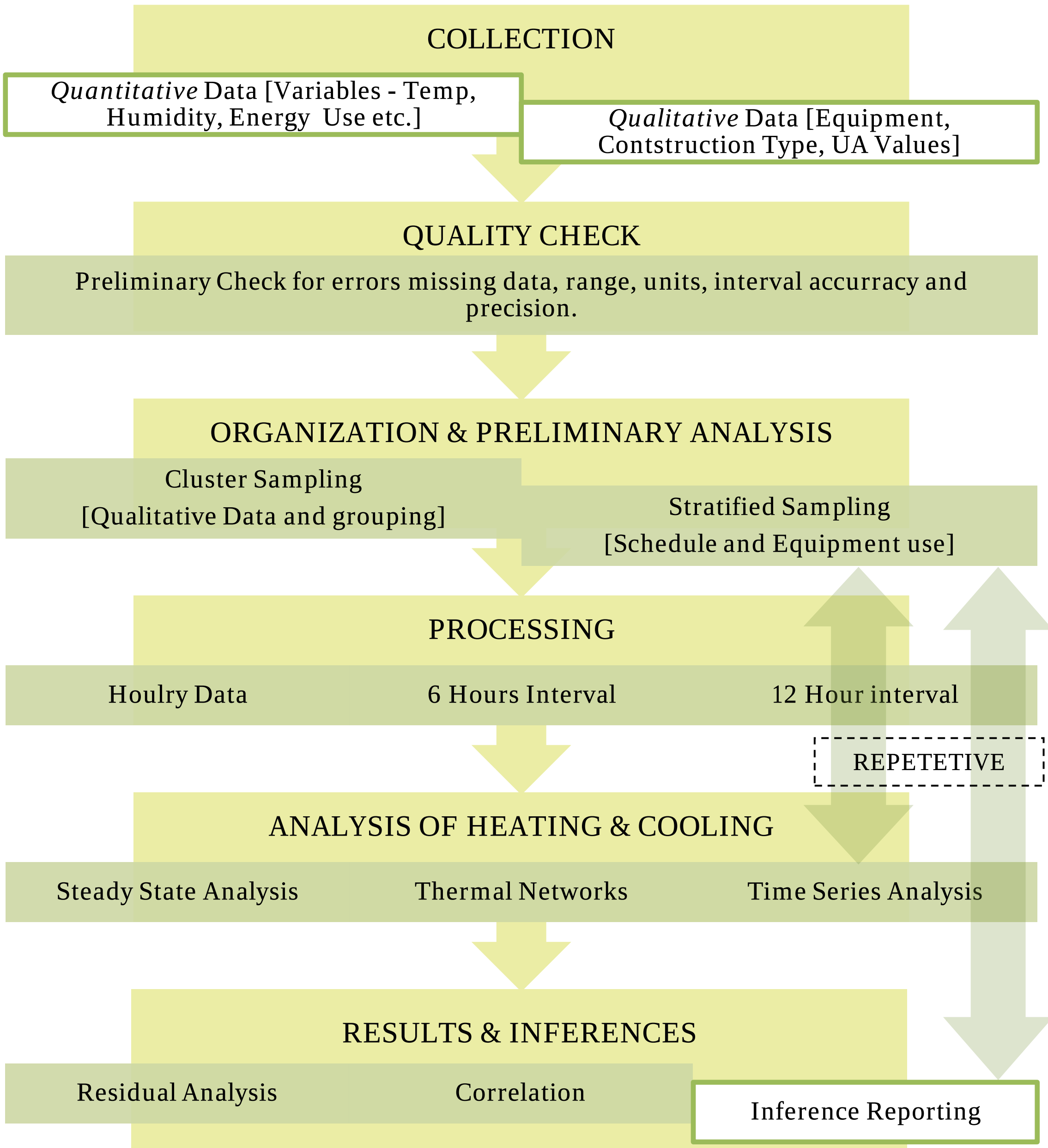


Figure 9: Flowchart Outline for the methodology of this thesis.

The process of this analysis can be broadly broken into six steps. It begins with Data collection and quality checks where the two quantitative and qualitative data provided by the DOE is collated and organized into a spreadsheet - described in 4.2. The next phase is preliminary analysis where the data is preprocessed through sampling into segregated energy by end uses data that is organized to allow isolation of the HVAC energy use for further analysis in the next stage - explained in 4.3 and 4.4. During the sampling stage the data is also tested for outliers and modified to gain better control of the analysis. The results from the analysis are later tested to determine nature of correlation and significance of the forecast model -described in 4.5.

4.2 Data Collection and Quality Check

The US Department of Energy guidelines on collection of data during the competition were very specific, common to all contestants and regulated by the organizing team from National Renewable Energy Laboratory (NREL).

Quantitative Data: Data was scrutinized through *observation* and *descriptive statistics* and *conditional formatting* in a spreadsheet. First order of checks was for *range*, *interval* and *nature of data* - units, precision and accuracy. Second order of checks revealed the frequently occurring problem of loss of signal therefore leading to patches of *missing data* in the population. Apart from missing data there were few *instances of inaccurate readings* on channels.

Qualitative Data: This step was mining for data from the manual of specifications and the construction documents provided by the teams for the construction type and UA values, Areas, WW Ratios, equipment/ technology are used. For example, whether they used an air based or water based primary and if it was forced air or radiant circulation cooling technologies or hybrid systems, and if the water heating was electric coil, solar, heat pump or hybrid etc.

Error checking - Steps were followed in this order to remedy errors in the data.

1. Wherever possible an instantaneous average from multiple channels recording the same data variable was used while omitting the missing data.
2. For variables like temperature and humidity if the missing data was not more than eight intervals then a fitted curve for the local sixteen readings before and after the missing patch were used to fill in the data.
3. For missing or incorrect readings data that were scattered an instantaneous average from other prototypes was used as a substitute.
4. For very large continuous sets and grossly incorrect readings - data for that time series was removed from the study across all variables for all experimental units.
5. Finally as check throughout the study and to allow greater control of data at these stage, outliers with (Z-score > 3) were replaced by the reading = $\mu + 3\sigma$.

4.3 Organization and Sampling

The quantitative data received from DOE was the total energy consumed and total energy generated. This did not have a breakdown of energy consumption by end-use. Therefore an exhaustive effort to segregate this data was necessary.

1. Correlation - expressed as a table 5.3 - between schedule of contest and the appliance expected to be engaged during that schedule was created.
2. *Sampling I* - Based on the Qualitative data and *cluster sampling* technique [refer 3.5.1] three groups depending on the technology of heating and cooling equipment were formed and comprised of the teams that had technology similar to each other.
3. *Sampling II* - This stage required stratification of data based on energy consumption by appliance - lights, refrigerator, dishwasher, washer dryer, Air-

conditioner water heater, pumps and miscellaneous plug loads. Using *strata sampling* technique [refer 3.5.1] a segmented map of the energy consumption per contest was generated based on the schedule of the contest.

4. *Segregation* - using the table from step 1 - with association of appliance to the contests and energy consumption map from step 3, an exhaustive matrix was created that allowed segregation of energy consumption during the contest to its appliance.

5. Based on the total energy use data, schedule of use and the segregated energy-consumption by end use, HVAC end-use could be isolated.

4.4 Analysis and Repetition

The analysis process from here on was a repetitive trial and error method to establish correlations between the predictor variable - OA temperature (that effects the cooling and heating load), and the response variable Energy Use of the HVAC. There were three Inverse models chosen to compare the data - steady state, thermal network with single node and time series based visual analysis - to understand the nature of correlation. [Refer section 3.4].

As discovered during the study - the spread of the data points creates unnecessary biases due to extreme noise and offer at best a weak correlation. Therefore after the initial study when hourly data analysis proved to be inconclusive - retrials of similar analysis were performed with 6 hourly intervals and 12 hourly intervals of data.

4.5 Usefulness and Inference

To analyze the results of the regression by checking usefulness of the regression equation using coefficient of determination and analysis of the residuals [refer 3.5.4 and 3.5.5]. Post analysis a commentary is made about the slope (positive / negative) and the character (weak / strong) of the regression equation, and therefore infers the relationship between the predictor and the response variable.

CHAPTER 5

PRELIMINARY ANALYSIS OF DATA

5.1 Description of Experimental Units

To keep the description of the competition houses brief and relevant to the study a summary of the building components - construction type, lighting, and the equipment will be presented. The competition houses exhibit technology and design intent that can easily be considered as exceeding the suggested ECMs by the HUD and ASHRAE as is apparent from collated data presented in the following text. [refer section 2.3 for HUD and ASHRAE suggestions]

1. Building Envelope [B] - Table -3 highlights some of the insulation values and glazing as observed in a few houses that participated in the 2013 version of the competition. On an average, the roof insulation ranges from R35 -R60. Contrast this to the ASHRAE 90.1 2010 vintage recommended roof insulation for Zone 3 at R35. This is a 30 % increase in R-Value.

In an attempt to outperform in the thermal insulation department while keeping the systems cost effective, there was a variety of unconventional exterior wall systems on display. Some common techniques used were Structurally Insulated Panels (SIPs) with special radiant reflective coatings and paint, SIPS with cladding that hugged the substructure, SIPs with cladding that was a separate skin, Insulated concrete, staggered studs with shade skin, dual and triple screen systems, green screens and even combination of some of these.

Nearly all prototype houses had large window wall ratio exceeding 35% but were mostly shaded from direct solar gain from the South, East and the West. There were low thermal emissivity - high performance glass in windows and some houses had thermally broken window and door frames to minimize thermal bridging. The building envelope was further shaded from direct solar gain, in some cases through screens.

		INSULATION			
		ROOF	WALLS	FLOOR	WWR
Alberta	BOREALIS	38	40	28	35%+
ASU / UNM	SHADE	55	40	30	35%+
Capitol DC	HARVEST	38	20	19	--
Kentucky Indiana	PHOENIX HOUSE	60	33	20	--
Las Vegas	DESERTSOL	55	30	45	--
North Carolina	URBAN EDEN	55	30	30	--
Sci-Arc Caltec	DALE	30	23	24	--
Stevens	ECOHABIT	46	34	34	--

Table 3: Insulation Data from Contestants - Values for the building envelope.

2. Mechanical Systems [H] - Like the advanced building envelope, there were a variety of heating and cooling systems on display. While the long term performance and efficiency of some of the novelty systems remain to be seen, there were two common themes in all systems; a better control system and thermostat response and high performance energy recovery systems and heat exchangers.

As a first step in preliminary analysis - *cluster sampling* [section 3.5.1] I had to broadly categorize these systems in the conventional cannons of Air- Based and Water- Based systems. Within these there were examples of combination of HVAC equipment -

conventional chillers, multi staged scroll chillers, Hybrid heat pumps, economizers, high velocity diffusers, desiccant systems, Energy Recovery Ventilators ERV, and other Heat recovery equipment etc.

In the table below an attempt is made to broadly classify the various systems that were on display. Enthusiasts can perhaps obtained detailed blueprints for the design from the participant teams.

Team Name	House	Mechanical System
Alberta	BOREALIS	AIR-BASED HIGH VELOCITY AIR HANDLER
Arizona State/ New Mexico	SHADE	HYBRID WATER BASED SCROLL WATER CHILLER + RADIANT DISTRIBUTION BEKA MATS + FAN COIL + ERV
Capitol DC	HARVEST	AIR-BASED HEAT PUMP CENTRAL AIR-HANDLER WITH DUCTED DISTRIBUTION.
Kentucky Indiana	PHOENIX HOUSE	AIR BASED WTH ECONOMIZER
Las Vegas	DESERTSOL	AIR BASED SPLIT SYSTEM + ERV
Middlebury	INSITE	AIR BASED SPLIT SYSTEM + ERV
Missouri S and T	CHAMELEON	AIR BASED SPLIT SYSTEM + ERV
North Carolina	URBAN EDEN	AIR BASED SPLIT SYSTEM AIR/ AIR + SOLAR THERMAL - RADIANT HEATING IN WALLS
Ontario	ECHO	AIR BASED SOLAR ASSISTED HEAT PUMP + ERV
Santa Clara	RADIANT HOUSE	HYBRID WATER BASED MODULAR CHILLED CEILING + MINI SPLIT
SciArc Caltec	DALE	AIR BASED HEAT PUMP WITH 2 INDOOR TERMINALS
Stanford	START.HOME	AIR BASED TRI ZONE MINI SPLIT + ERV
Stevens	ECOHABIT	AIR BASED SPLIT SYSTEM
University of Southern California	FLUXHOME	AIR BASED HEAT PUMP + INDOOR TERMINAL

Table 4: Mechanical Equipment Data provided by contestants.

3. Water Heating [W] - Similar to the mechanical system there were a combination of systems at display. These could be categorized into solar thermal, solar thermal hybrid,

hybrid (heat pump), or on demand. There were many teams that had multiple water heating systems on display.

House	DHW
BOREALIS	SOLAR THERMAL + ELECTRIC COIL
SHADE	HYBRID HEAT PUMP + ELECTRIC COIL
HARVEST	HYBRID - FLAT PLATE SOLAR THERMAL + AUXILLARY ELECTRC COIL
PHOENIX HOUSE	ELECTRIC COIL WATER HEATER
DESERTSOL	SOLAR THERMAL + ELECTRIC COIL INSTANT
INSITE	ELECTRIC COIL WATER HEATER
CHAMELEON	ELECTRIC COIL WATER HEATER
URBAN EDEN	HEAT PUMP HOT WATER + SOLAR WATER
ECHO	SOLAR THERMAL + AUXILLARY ELECTRIC COIL INSTANT
RADIANT HOUSE	HEAT PUMP WATER HEATER WITH AUXILLARY ELECTRIC COIL AND BUILT IN BOOSTER PUMP
DALE	SOLAR THERMAL EVACUATED TUBES
START.HOME	ELECTRIC COIL + HEAT PUMP
ECOHABIT	HYBRID HEAT PUMP+ ELECTRIC COIL
FLUXHOME	SOLAR THERMAL + HEAT PUMP + ELECTRIC COIL

Table 5: Domestic Hot Water Equipment provided by contestants.

4. Lighting [L] and Miscellaneous [Msc] - This was an expected segment with most teams opting for LED lighting with central and sometimes automated control systems. The appliances were all high efficiency appliances with European teams exceeding in that department.

5.2 Description of Measured Data

Stand- alone weather stations dedicated to collection of outside air temperature, humidity, solar radiation, wind speed, direction at multiple locations on site. For each team there were multiple channels dedicated for collection of temperature and humidity inside the homes based number of zones in each zone. (Table 5.2)

For the energy balance competition, energy consumption data was collected through a grid-tied two way net meter. To ensure the base minimum usage as per the schedule and enforce the common criteria for performance of the appliances, the scheduled measured contest were monitored through sensors placed in refrigerator, dishwashers, washer and dryers and also visually inspected during the contest duration. Following in table 6 is a sample of the data that was collected through these sensors.

	Wireless Sensors : 0=Not Used , 1=Used							
	T&RH 1	T&RH 2	T&RH 3	T&RH 4	Tonly 1	Tonly 2	Tonly 3	Tonly 4
Datalogger Serial Number	Indoor 1	Indoor 2	Indoor 3	Indoor 4	Fridge 1	Fridge 2	Freezer 1	Freezer 2
40342	1	1	1	0	1	0	1	0
40348	1	1	1	0	1	0	1	0
40347	1	1	0	0	1	0	1	0
40350	1	1	0	0	1	0	1	0
40346	1	1	1	0	1	0	1	0
40351	1	1	0	0	1	0	1	0
40343	1	1	0	0	1	0	1	0
40349	1	1	0	0	1	0	1	0
40354	1	1	0	0	1	0	1	0
40359	1	1	1	0	1	0	1	0
40345	1	1	1	0	1	0	1	0
40353	1	1	0	0	1	0	1	0
40344	1	1	1	0	1	0	1	0
40355	1	1	0	0	1	0	1	0
40356	1	1	0	0	1	0	1	0
40358	1	1	1	1	1	0	1	0
40357	1	1	1	0	1	0	1	0
40341	1	1	1	0	1	0	1	0
40352	1	1	1	0	1	0	1	0
40340	1	1	1	0	1	0	1	0

Table 6 - Matrix for the Collected Data - Variable Types (T&RH# and indoor# - Temperature and Humidity - sensor number 1, Indoor zone 1, the numbers 1 and 0 imply state of operation)

The collected quantitative data required instrumentation (sensors and data loggers) stipulated by DOE- details of which are available in Appendix A.7. The NREL algorithms converted the received logger signals to a Quasi - processed state. All channels had a frequency set to 5 minute and were recording data at 15 minute intervals.

Time Stamp	Count	Team Name	S1	S2	S3	S4
10/3/2013 11:45	452	Sci_Arc_Caltech	12	14	13	0
10/3/2013 12:00	453	Sci_Arc_Caltech	15	15	13	0
10/3/2013 12:15	454	Sci_Arc_Caltech	14	12	14	0
10/3/2013 12:30	455	Sci_Arc_Caltech	13	14	13	0
10/3/2013 12:45	456	Sci_Arc_Caltech	14	14	13	0
10/3/2013 13:00	457	Sci_Arc_Caltech	15	15	13	0
10/3/2013 13:15	458	Sci_Arc_Caltech	13	14	13	0

Table 7 - Sample of the collected data from the sensors

Table 6 and 7 above are sample of the collected data recorded as packets of information received in 15 minute intervals and shared by DOE as quantitative data in its raw form as spreadsheets. Figures 10 and 11 has temperature and the energy balance data from the duration of the competition as time series graphs.

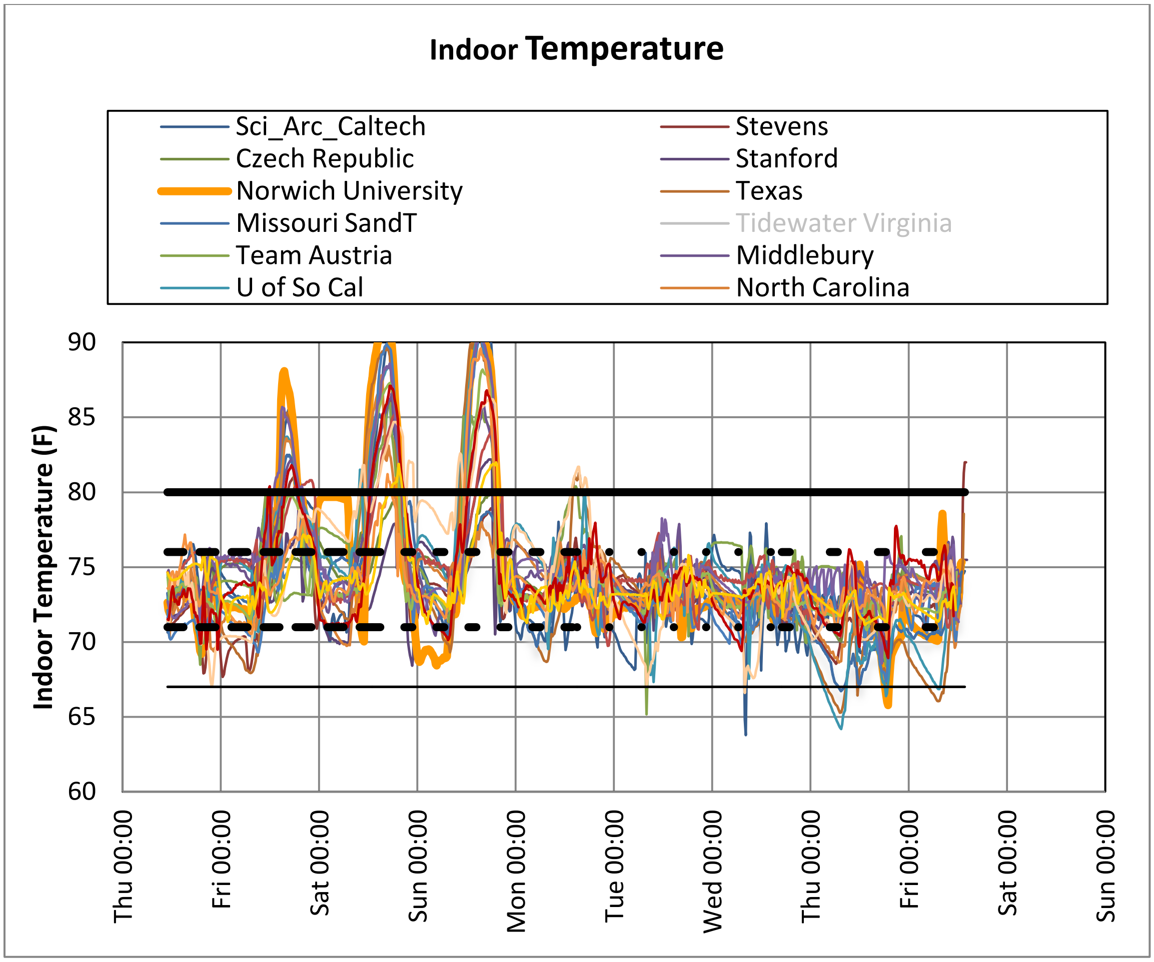


Figure 10 Temperature signatures.

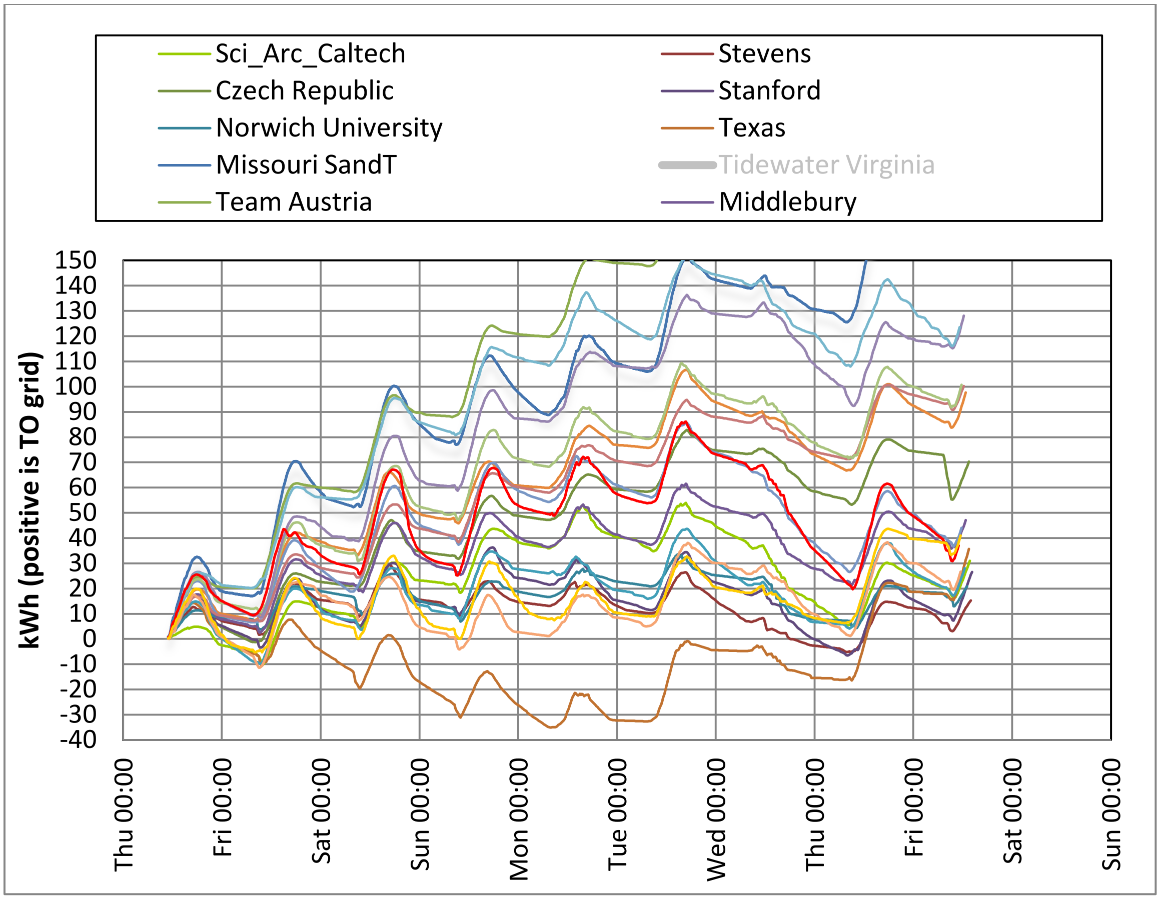


Figure 11 - Energy Balance signature.

5.3 Segregation

Stage 1: Cluster Sampling. - Based on the Qualitative data discussed in section 5.1, the following HVAC equipment based groups were formed. For the sake of accurate comparison based on the equipment nameplate energy use and power draws, the European teams were ignored from this study. [Appendix A.8 Illustrates detailed matrix of the building components and end use appliances data available.]

GROUP A: Air Based HVAC primary Equipment + Heat pump Based HW

GROUP B: Air Based distribution (cooling), Radiant Heating + Solar Thermal

GROUP C: Radiant Cooling and Heating Distribution and Supplementary Fan Coil

Group A	Ken-Ind	PHOENIX HOUSE
	Middlebury	INSITE
	Missouri S&T	CHAMELEON
	Stanford	START HOME
*	Stevens	ECOHABIT
Group B	Alberta	BOREALIS
	Capitol DC	HARVEST
	Las Vegas	DESERT SOL
	N Carolina	URBAN EDEN
	Ontario	ECHO
	Univ. SoCal	FLUXHOME
	SciArc CalTec	DALE
Group C	Santa Clara	RADIANT HOUSE
	ASU/ UNM	SHADE

Table 8 Cluster formatted team groups - based on their Cooling and Heating Systems Technology.

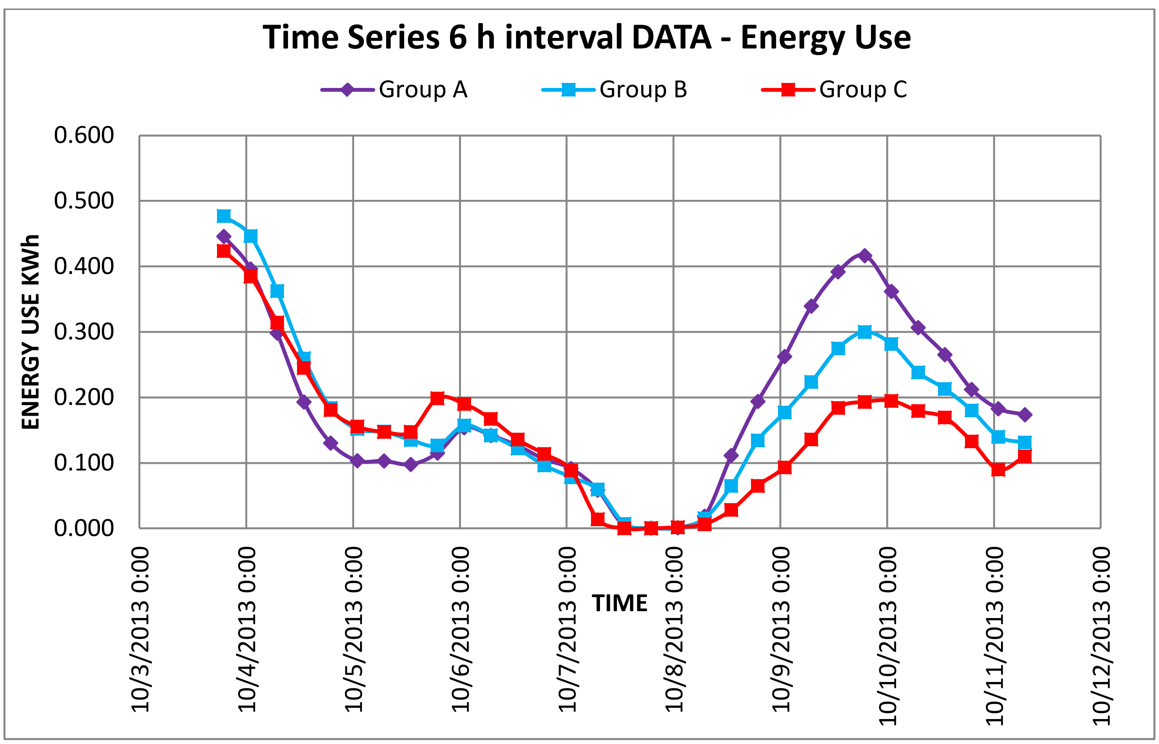


Figure 12 Six Hour whole building energy signatures for the three group's revealed moderate congruence with cluster sampling logic.

Stage 2 : Stratification - To best explain this process as mentioned in 4.3, I would first like to describe the contest schedule - Figure 13a and figure b shows partial example of two days (12) and (13) and then later days (17) and (18). This was common and binding to all teams. The schedule requires the teams to begin using a certain appliance associated with that contest and operate them uninterrupted for the number of hours stipulated in the schedule. For example on day 12 Wednesday, all the teams had to have all their house lights switched on between 8:00 to 11: of pm.

Notice while there are a few isolated events where the energy use data is recording of a single appliance -(refrigerator - perhaps cycling) most of the data points per 15 minute interval are in reality a combination of multiple events like operation of dishwasher and-or electronics.

There were two strategies discussed for stratification - first to use the combined energy use as a singular energy signature and stratify energy use based on the 'time of the day' or the number of uninterrupted use. A second strategy was to understand the composition of each of these combinations and use partition theory to isolate and extract individual specific energy signatures of the appliance or equipment being used inside. Due to the shortness of time frame of the collected data, the use of first strategy to stratify meant that a lot of assumptions will be necessary for the analysis to reflect a year. Furthermore, influenced by the Component Isolation Approach - also mentioned in the International Performance Measurement and Verification Protocol (IPMVP) as a suggested procedure to evaluate energy performance if the annual utility data and the daily energy measurement use are not dependable - segregation was done using the second strategy.

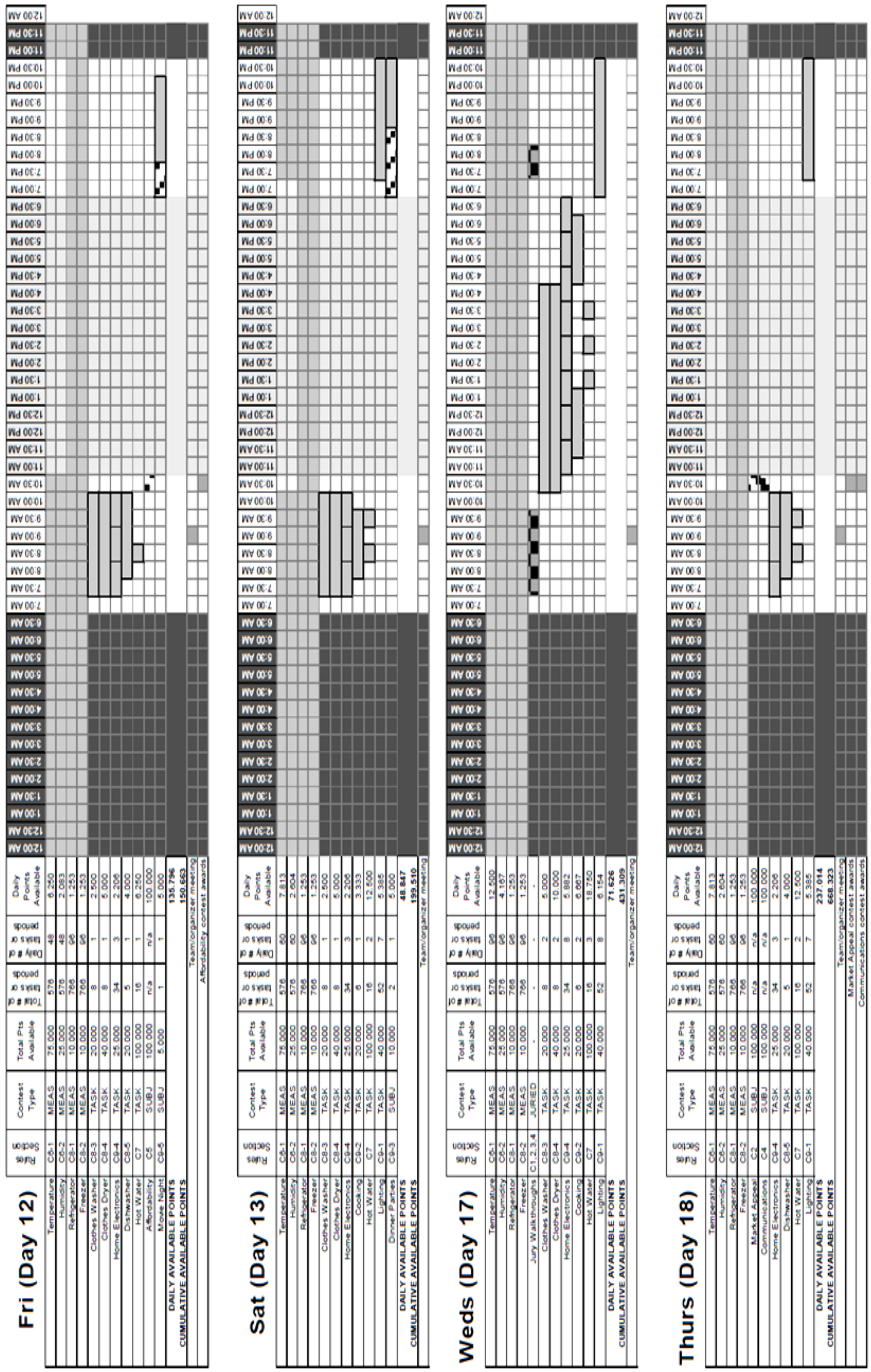


Figure 13a : Sample of schedule of the contests.

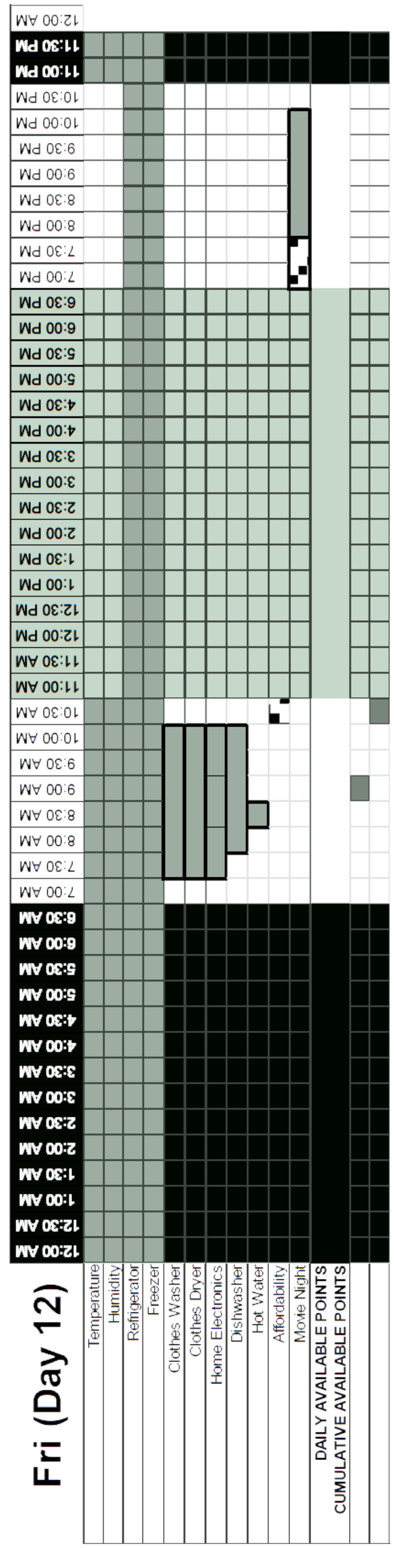


Figure 13b : Enlarged view of figure 13a sample schedule of the contests.

DOE - CONTEST	Comfort System	Hot Water Draw			Cooking	Appliance (plugged)	Hot Water Draw	Clothes washing /drying	
EVENT TIME	AIR COND	WATER HEATER	REFRIDG .	LIGHTS	RANGE/ OVEN	ELEC APPL	PUMP	WASHER DRYER	DISH WASHER
ASSIGNED VARIABLE	X1	X2	X3	X4	X5	X6	X7	X8	X9
10/3/2013 19:00	1	1	1	1					
10/3/2013 19:15	1	1	1	1					
10/3/2013 19:30	1	1	1	1					
10/3/2013 19:45	1	1	1	1	1				
10/3/2013 20:00	1	1	1	1	1				
10/3/2013 20:15	1	1	1	1	1				
10/3/2013 20:30	1	1	1	1	1				
---------------------- ----------cut-------- ----------------------									
10/4/2013 9:00	1	1	1			1		1	1
10/4/2013 9:15	1	1	1			1		1	1
10/4/2013 9:30	1	1	1			1	1	1	1

Table 9 - Extraction of the equipment end-use [The number 1 only represents that the appliance was active and is there only there to count the number of packets of reading]

Table 9 above is an abridged section of the extracted data with the contests, their associated appliance and assigned variable at columns and the time -stamp record of the energy use through a 15 minute interval of that appliance per the DOE schedule in the rows.

This process made it easier to identify the combinatorial groups and assign a specific reading to that combination. An example is the first row in the table with time stamp 10/3/2013 19:00 where the energy consumption reading could have only been X1 - X4. Based on such grouping, a detailed map was created for the entire nine day data set. This exhaustive process was done for all 14 experimental units as the initially segregated groups A, B and C. Table 5.3.3 [- pg 45] is an example of such an organized data for one team - this table has one other process of *outlier elimination* which is discussed next.

A closer look at the energy use data and readings show instances where within a small consecutive sub set of data there are a few readings that have a arbitrarily high variation from the local mean of that subset when compared with the variations of their immediate preceding and succeeding recorded data points. This is unexplained, an expected local subset would have readings that are similar to each other in magnitude, instead the occurrence of such erratic readings in an overall uniform local subset highlights the 15 minute demands in the energy use as if there is cycling of equipment. To understand this phenomenon and its effect it is important to understand the magnitude of deviation and the reasons that may have caused them.

Such isolated spikes and dips where examined within their immediate local energy -use data segments (partial graph) during a specific scheduled event. This was done by *standardizing* the interval reading into *Z-variables* that could monitor the deviation in the reading when compared to the average of instantaneous interval readings across all teams. The reasons for high deviation of some readings could possibly be either an unrealistic value (incorrect reading) or a sudden spike caused due to cycling of some equipment (perhaps - electric coil in the water heater, or compressors in AC or refrigerator). An example of this process of standardizing and outlier elimination is shown in sample data show in Figure 14 and Figure 15. These are the event by appliance use schedule as discussed earlier and a graph for the segmented 15 min energy use interval data for those specific events.

Event Time	A/C	HW	REF	LIT	R/O	E/A	PU	W/D	DW
10/5/2013 4:00									
10/5/2013 4:15									
10/5/2013 4:30									
10/5/2013 4:45									
10/5/2013 5:00									
10/5/2013 5:15									
10/5/2013 5:30									
10/5/2013 5:45									
10/5/2013 6:00									
10/5/2013 6:15									
10/5/2013 6:30									
10/5/2013 6:45									
10/5/2013 7:00									
10/5/2013 7:15									
10/5/2013 7:30									
10/5/2013 7:45									
10/5/2013 8:00									

Figure 14 - Appliance use Matrix [4:00 - 8:00 am - 10/05]

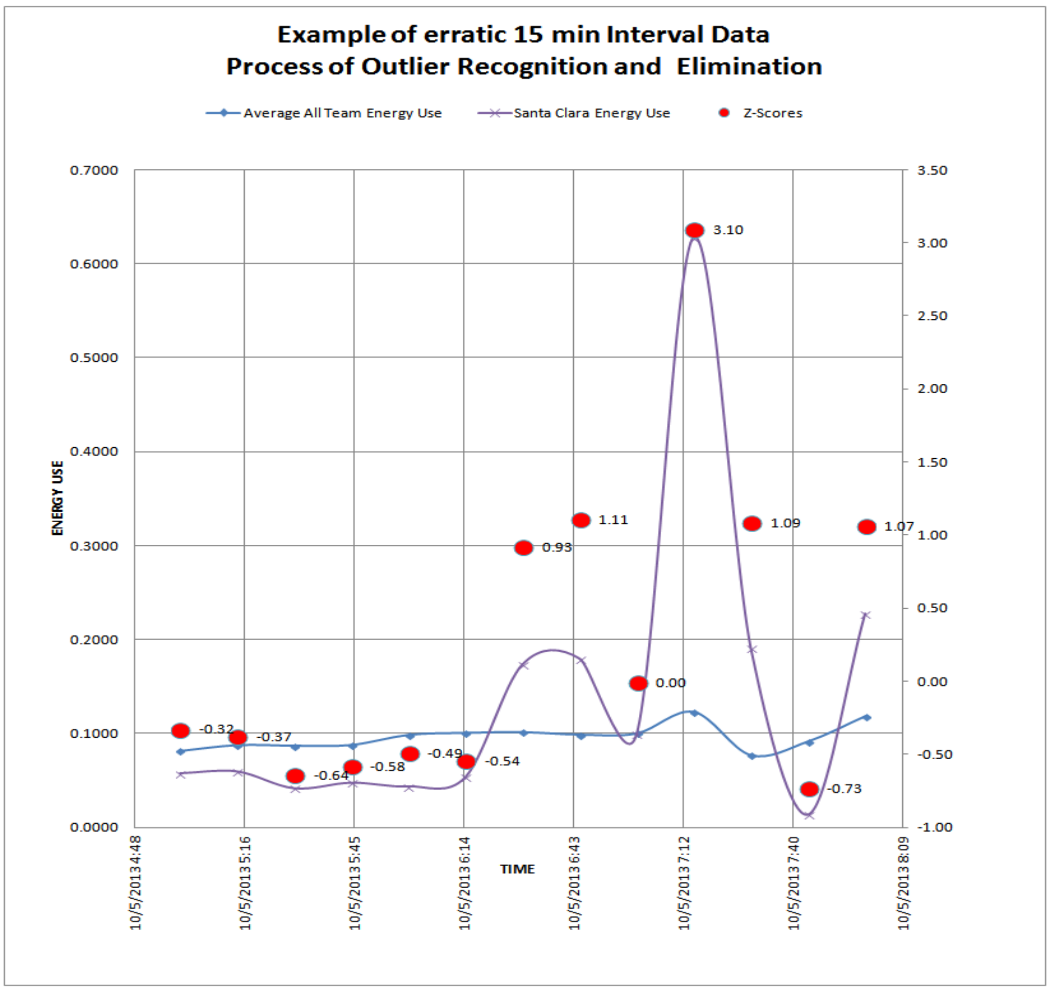


Figure 15 - Outlier elimination - graphs of data from figure 14.

NOTE: The spike/ dips in energy signature in most cases required in-depth examination and could not be explained through a peripheral analysis; therefore as a strategy to control data for the forthcoming study all extreme outliers were replaced with an equivalent of their standardized $\pm$ 2.5 Z score. This, while allowing the study a more streamlined and tighter data set, also ensured to preserve the local trends retaining visually the accurate ups and downs of the energy use data as response to the event schedule.

Table 11 is an example of single team's data organized after it was contrast with the event schedule from figure 13 to reflect the combined energy - end-uses as stratified variables.

BOREALIS	X1	X2	X3	X4	X5	X6	X7	X8	X9	Avg. All Teams	Energy Use	STD DEV	Z SCR	X1 + X2 + X3	X3	X2 + X3	X123+ X4	X123+ X4+X5	X123+ X6+X8	X123+ X6789	X2+X3+ X4	X2+X3+ X4+X5	X2+X3 +X6	X123+ X56789	X123+ X678	X123 +X6	X123+ X6+X8 +X9	X123+ X5+X6	X123 +X5
Event Time	A/C	HW	REF	LIT	R/O	E/A	PU	W/D	DW																				
10/3/2013 18:30										0.1142	0.0480	0.096	-0.69	0.0480															
10/3/2013 18:45										0.1509	0.0860	0.116	-0.56	0.0860															
10/3/2013 19:00										0.2398	0.2160	0.207	-0.11				0.2160												
10/3/2013 19:15										0.3344	0.3660	0.198	0.16				0.3660												
10/3/2013 19:30										0.3845	0.4020	0.283	0.06				0.4020												
10/3/2013 19:45										0.4833	0.4020	0.276	-0.29					0.4020											
10/3/2013 20:00										0.4834	0.2520	0.330	-0.70					0.2520											
10/3/2013 20:15										0.5578	0.3980	0.337	-0.47					0.3980											
10/3/2013 20:30										0.6589	0.7940	0.386	0.35					0.7940											
10/3/2013 20:45										0.6652	0.6020	0.374	-0.17					0.6020											
10/3/2013 21:00										0.8056	1.3060	0.412	1.22					1.3060											
10/3/2013 21:15										0.6900	1.1100	0.313	1.34					1.1100											
10/3/2013 21:30										0.6566	0.5300	0.252	-0.50					0.5300											
10/3/2013 21:45										0.5200	0.5660	0.236	0.20					0.5660											
10/3/2013 22:00										0.4578	0.5600	0.186	0.55					0.5600											
10/3/2013 22:15										0.4932	0.5820	0.246	0.36				0.5820												
10/3/2013 22:30										0.5178	1.0600	0.245	2.21				1.0600												
10/3/2013 22:45										0.4759	0.7300	0.191	1.33				0.7300												
10/3/2013 23:00										0.4347	0.6580	0.213	1.05				0.6580												
10/3/2013 23:15										0.2329	0.2360	0.164	0.02	0.2360															
10/3/2013 23:30										0.1922	0.2200	0.159	0.17	0.2200															
10/3/2013 23:45										0.1769	0.2080	0.119	0.26	0.2080															
10/5/2013 5:30										0.0873	0.0200	0.071	-0.95	0.0200															
10/5/2013 5:45										0.0880	0.0600	0.069	-0.40	0.0600															
10/5/2013 6:00										0.0988	0.4460	0.112	3.09	0.0988															
10/5/2013 6:15										0.1009	0.3240	0.087	2.56	0.3240															
10/5/2013 6:30										0.1016	0.2760	0.078	2.23	0.2760															
10/5/2013 6:45										0.0991	0.1720	0.073	1.00	0.1720															
10/5/2013 7:00										0.1004	0.0360	0.092	-0.70	0.0360															
10/5/2013 7:15										0.1232	0.0100	0.163	-0.69	0.0100															
10/5/2013 7:30										0.0772	0.0000	0.105	-0.73						0.0000										
10/5/2013 7:45										0.0918	0.0180	0.107	-0.69						0.0180										
10/5/2013 8:00										0.1186	0.0000	0.102	-1.16							0.0000									
10/5/2013 8:15										0.3301	0.3440	0.281	0.05							0.3440									
10/5/2013 8:30										0.5156	0.2100	0.433	-0.71							0.2100									
10/5/2013 8:45										0.7749	0.0440	0.574	-1.27							0.0440									
											AVERAGE			0.1014	0.0072	0.2087	0.4177	0.8058	0.0398	0.0912	0.0230	0.0750	0.1451	0.3613	0.1179	0.0000	0.2326	0.5713	0.09

Table 10 - Organized energy use data with combined variables as stratums.

5.4 Determining Equipment Energy Use

The organized data for all the teams is collated as averages of energy use per contest - scheduled event with the previously derived combinations of the energy consumption by end-use. [Refer table 11 - Collated Data]. From here the task is to isolate the X1 energy signature.

The intention here is not to evaluate each and every variable to accuracy but rather to isolate the HVAC electric energy use - variable X1 from the given matrix. This is important since X1 is the only variable or part of the response variable that has external predictor variables that we are interested in (temperature, humidity) - the water heater is another variable and it can be argued that the refrigerator operation, cooking , occupancy can all be a factors - yes. However, after looking at the contesting team's high efficiency - hybrid and solar water heating equipment and a very disciplined refrigerator/ appliance operations throughout the competition, it can be said with relative confidence that the energy signatures of these appliances were reasonably consistent per group (A, B and C) during the contests and therefore that the variable X1 A/C- through its swings - is the prime contributing variable that can distinguish the teams within their groups.

HOUSE	X1	X3	X2 + X3	X123+ X4	X123+ X4+X5	X6+X8	X6789	X2+X3+ X4	X2+X3+ X4+X5	X2+X3 +X6	X123+ X56789	X123+ X678	X123 +X6	X123+ X6+X8+X 9	X123+ X5+X6	X123 +X5
PHOENIX HOUSE	0.1613	0.0016	0.2434	0.4553	0.8453	0.0882	0.0908	0.2030	0.7500	0.4369	0.5340	0.3114	0.0000	0.1035	0.6624	0.523
INSITE	0.1113	0.0024	0.1897	0.3627	0.6377	0.0170	0.3120	0.0565	0.3540	0.3198	0.3885	0.4202	0.0000	0.1748	0.5909	0.13
CHAMELEON	0.1327	0.0001	0.2530	0.4113	0.7545	0.0628	0.1386	0.1435	0.6755	0.5685	0.2897	0.1818	0.0000	0.0096	0.3984	0.408
START HOME	0.1208	0.0015	0.2973	0.4499	0.7699	0.0380	0.2322	0.0640	0.7005	0.5827	0.4357	0.3575	0.0000	0.0448	0.4851	0.5035
ECOHABIT	0.0994	0.0024	0.3763	0.2330	0.3988	0.1113	0.2782	0.0590	0.3055	0.3607	0.5253	0.1272	0.0000	0.0327	0.4436	0.466
BOREALIS	0.1014	0.0072	0.2087	0.4177	0.8058	0.0398	0.0912	0.0230	0.0750	0.1451	0.3613	0.1179	0.0000	0.2326	0.5713	0.085
HARVEST	0.0898	0.0064	0.2141	0.4375	0.7171	0.0128	0.2445	0.0425	0.3865	0.5471	0.4697	0.2375	0.0005	0.1470	0.5049	0.274
DESERT SOL	0.0665	0.0001	0.0828	0.2445	0.5216	0.0418	0.1168	0.0545	0.2250	0.2778	0.4253	0.1426	0.0000	0.0276	0.4469	0.155
URBAN EDEN	0.0939	0.0004	0.3846	0.4066	0.7215	0.0105	0.1281	0.0245	0.2300	0.1435	0.3389	0.1181	0.0000	0.0178	0.5393	0.407
ECHO	0.1023	0.0022	0.3159	0.4386	0.9286	0.1320	0.3113	0.1266	0.8245	0.6829	0.5282	0.1945	0.0000	0.0422	0.2539	0.486
FLUXHOME	0.1335	0.0015	0.2283	0.3891	0.9259	0.1150	0.2305	0.0730	0.2645	0.3011	0.4158	0.3357	0.0000	0.0618	0.4100	0.56
DALE	0.1213	0.0048	0.0642	0.2510	0.3396	0.0358	0.3756	0.0205	0.0690	0.1458	0.5841	0.4482	0.0000	0.1389	0.5943	0.461
RADIANT HOUSE	0.1312	0.0070	0.4853	0.4924	0.8461	0.1313	0.3121	0.0310	0.1570	0.1156	0.5449	0.1688	0.0000	0.0659	0.3777	0.2445
SHADE	0.1197	0.0021	0.1884	0.2712	0.3214	0.0533	0.0579	0.0240	0.1030	0.2905	0.4643	0.3262	0.0000	0.0477	0.3689	0.5065

Table 11 - Collated Data for all Teams

Isolation of these variables and substituting their instantaneous energy performance data with their group averages modifies the data set. It necessary to test this new modified data set. Prior to using this data it is necessary to identify the error range that will result in the derived value of X1 relative to the other end-use variables. This testing compares the inferred total energy use with the observed total energy use and evaluates the standard deviations of the errors that result from this. After this analysis we will be ready to use this modified data for the thermal analysis. Table 12 shows the testing exercise and is followed by Table 13 which is abridged extraction of the modified data for all variables except X1 for a single team.

	X1	X2	X3	X4	X5	X6	X7	X8	X9			
Total hours	**607**	**65**	**760**	**122**	**60**	**35**	**60**	**45**	**45**	OBSRVD	INFERED	Diff
PHOENIX HOUSE	0.161	0.242	0.002	0.071	0.469	0.194	0.068	0.431	0.102	177.508	177.074	0.434
INSITE	0.111	0.187	0.002	0.056	0.286	0.130	0.119	0.214	0.172	143.742	146.723	2.981
CHAMELEON	0.133	0.253	0.000	0.066	0.438	0.316	0.119	0.280	0.009	144.286	159.728	15.442
START HOME	0.121	0.296	0.001	0.071	0.478	0.285	0.060	0.391	0.043	157.478	152.511	4.967
ECOHABIT	0.099	0.374	0.002	0.035	0.206	0.261	0.075	0.219	0.025	115.54	139.513	23.973
BOREALIS	0.101	0.201	0.007	0.060	0.220	0.145	0.078	0.129	0.225	134.026	138.326	4.300
HARVEST	0.090	0.208	0.006	0.064	0.312	0.243	0.225	0.323	0.141	143.246	131.311	11.935
DESERT SOL	0.066	0.083	0.000	0.039	0.224	0.129	0.101	0.398	0.027	89.336	117.151	27.815
URBAN EDEN	0.094	0.384	0.000	0.065	0.260	0.143	0.108	0.321	0.017	123.942	133.772	9.830
ECHO	0.102	0.314	0.002	0.068	0.594	0.265	0.062	0.486	0.040	167.056	138.870	28.186
FLUXHOME	0.134	0.227	0.001	0.061	0.364	0.168	0.221	0.354	0.060	154.726	157.838	3.112
DALE	0.121	0.059	0.005	0.035	0.069	0.146	0.412	0.445	0.134	133.91	150.435	16.525
RADIANT HOUSE	0.131	0.478	0.007	0.072	0.240	0.116	0.038	0.479	0.059	165.27	161.878	3.392
SHADE	0.120	0.186	0.002	0.041	0.321	0.171	0.159	0.417	0.046	126.042	154.890	28.848

Table 12: Difference between inferred energy use and observed energy use

VARIABLE (KWh)	X2	X3	X4	X5	X6	X7	X8	X9	A
10/3/2013 19:15	0.025	0.002	0.060						0.086
10/3/2013 19:30	0.025	0.002	0.060						0.086
10/3/2013 19:45	0.025	0.002	0.060	0.309					0.395
Cut									
10/4/2013 7:15	0.025	0.002							0.027
10/4/2013 7:30	0.025	0.002			0.060		0.171		0.258
10/4/2013 7:45	0.025	0.002			0.060		0.171		0.258
10/4/2013 8:00	0.025	0.002			0.060	0.083	0.171	0.063	0.403
Cut									
10/11/2013 7:45	0.025	0.002			0.060		0.171		0.258
10/11/2013 8:00	0.025	0.002			0.060	0.083	0.171	0.063	0.403
10/11/2013 8:15	0.025	0.002			0.060	0.083	0.171	0.063	0.403

Table 13- Abridged sample of the end use isolated data.

NOTE : The above testing revealed that while the inferred energy use was within an acceptable deviation for most cases there were cases where the difference was unexpectedly high and could not be explained. Therefore, for such cases instead of using derived averages for X2-X9 their actual energy - end use data was used for the thermal analysis. Table 14 is an example of the final set of organized data prepared prior to embarking on the energy use performance analysis for X1.

		A			
		Ken-Ind		PHOENIX HOUSE	
TIME STAMP	TEMP (F)	TOTAL	TOTAL		TEMP
	OA	(X2:X9)	OBSRVD	X1	IA
10/3/2013 19:00	74.4	0.08645	0.2800	0.19355	70.6
10/3/2013 19:15	73.4	0.08645	0.4660	0.37955	70.8
10/3/2013 19:30	72.6	0.08645	0.4040	0.31755	71.3
Cut					
10/11/2013 6:15	55.5	0.02665	0.2640	0.23735	73.9
10/11/2013 6:30	55.3	0.02665	0.1180	0.09135	73.6
10/11/2013 6:45	55.2	0.02665	0.1300	0.10335	72.7
10/11/2013 7:00	55.1	0.02665	0.1320	0.10535	72.0

Table 14 X1 vs. Non HVAC Energy use - 15 minute interval.

CHAPTER 6

ANALYSIS AND DISCUSSION OF HEATING AND COOLING LOADS

6.1 Steady State Inverse Model

Energy Signature with whole building energy use as described in Section 3.4 is the simplest steady-state inverse model (refer Kreider et al. 2010). Graphs in Appendix A.9 are scatter plots of two example houses, randomly chosen from each group, with the whole building energy use regressed against outside air temperature (Hammarsten, 1987 model - Kreider 2010).

The hourly scatterplot for group A and B reveals in both cases that the data is extremely scattered and noisy. With such indistinguishable data it is difficult to comment with any certainty on the nature of correlation between the predictor variable temperature and the response variables energy use. Also, the intent here is to explore a specific end use - the HVAC. Therefore, as the next step, the segregated data - X1 variable from chapter 5 - is used with the simple steady state inverse model. Like the previous case with whole building data [Appendix A.9] regression is done for the hourly, 6 hourly and 12 hourly averaged data sets.The following can be noted from figure 16 and 17 about the example houses from Group A and B.

1. The hourly data for both the houses from group A and B have a null energy use reading (0.00 KWh) spread across the temperature range from 60 - 90 °F. This can be attributed to the pre-determined schedule of contest that prompted operation of the HVAC systems to be turned down during the visitor hours between 10:00 -19:00 on days 12, 13, 14 and 18.
2. Although the data is extremely scattered and that the 6 hours interval data begins to reveal some clusters. It was generally observed that the separation of clusters is more pronounced in examples from Group A.

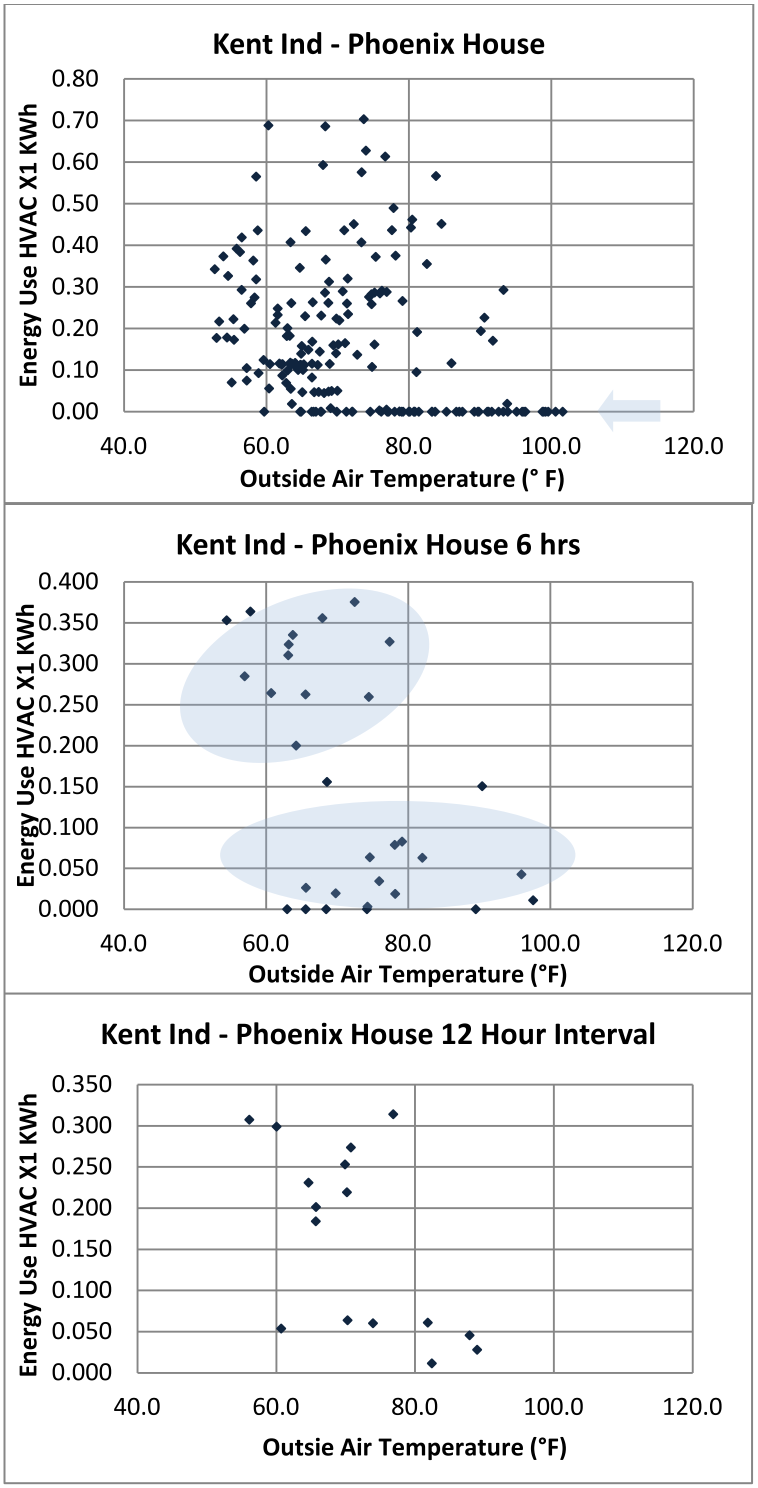


Figure 16: Group a - hourly, 6 hourly and 12 Hourly data.

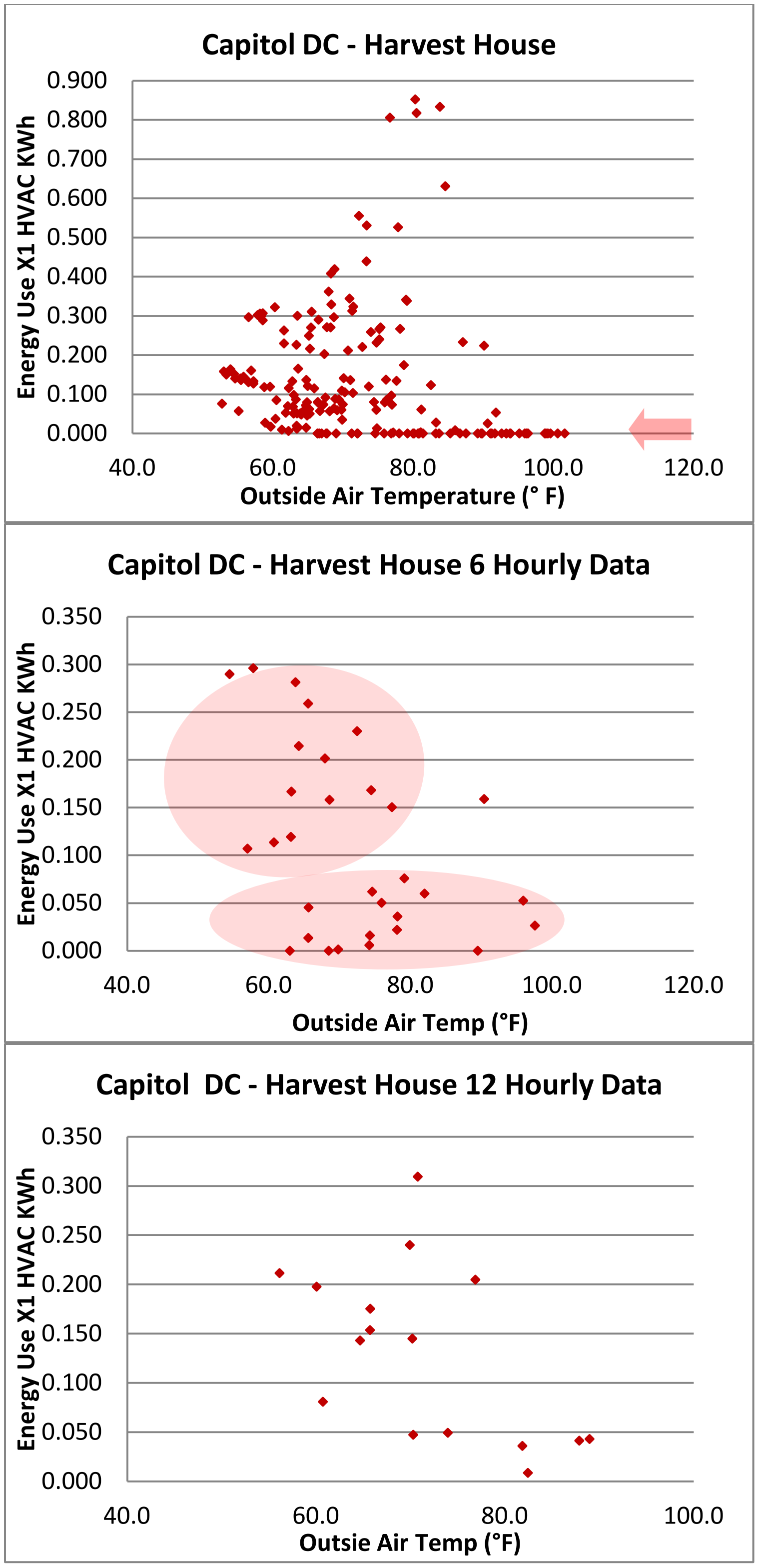


Figure 17 Group B - hourly, 6 hourly and 12 Hourly data.

Based on the above observations the next step in the analysis is to include time of operation of the HVAC systems and appliances as a parameter and consider the contest schedules.

Figures 18 and 19 are time series graphs similar to whole building time series graph discussed briefly in section 5.1 with added layer of complexity in outdoor and indoor temperature; the following can be noted from the data.

1. For houses in Group A and B alike; as observed earlier there is substantial overlap of the null readings during the break time for scheduled comfort contest during which perhaps the HVAC systems were turned down.
2. The outside air temperature was recorded above 80 ° F on only two brief occasions during the competition while the comfort contest was in effect. On average the temperature was 72.1 ° F during the entire duration of the competition and 67.7 °F during the time when the comfort contest was in effect - implying that the comfort systems were heated more than they cooled.
3. There are a few periods of 0.00 readings in most houses while the comfort contest was in effect and in all cases the additional null readings coincide with the increase in the outside Air temperature.[To be discussed in detail later]
4. The HVAC energy-use data as inferred from isolated X1 data between 19:00 October 06, 2013 - 10:00 October 10, 2013 suggests cycling in both cases represents predominantly heating and a few peaks for cooling energy use data but most significantly is the only continuous uninterrupted HVAC energy use data that can be split into occupied and unoccupied data. In general the data observed from group A is more erratic than in B.
5. The high peaks of outside air temperature were followed by peaks in HVAC energy use.

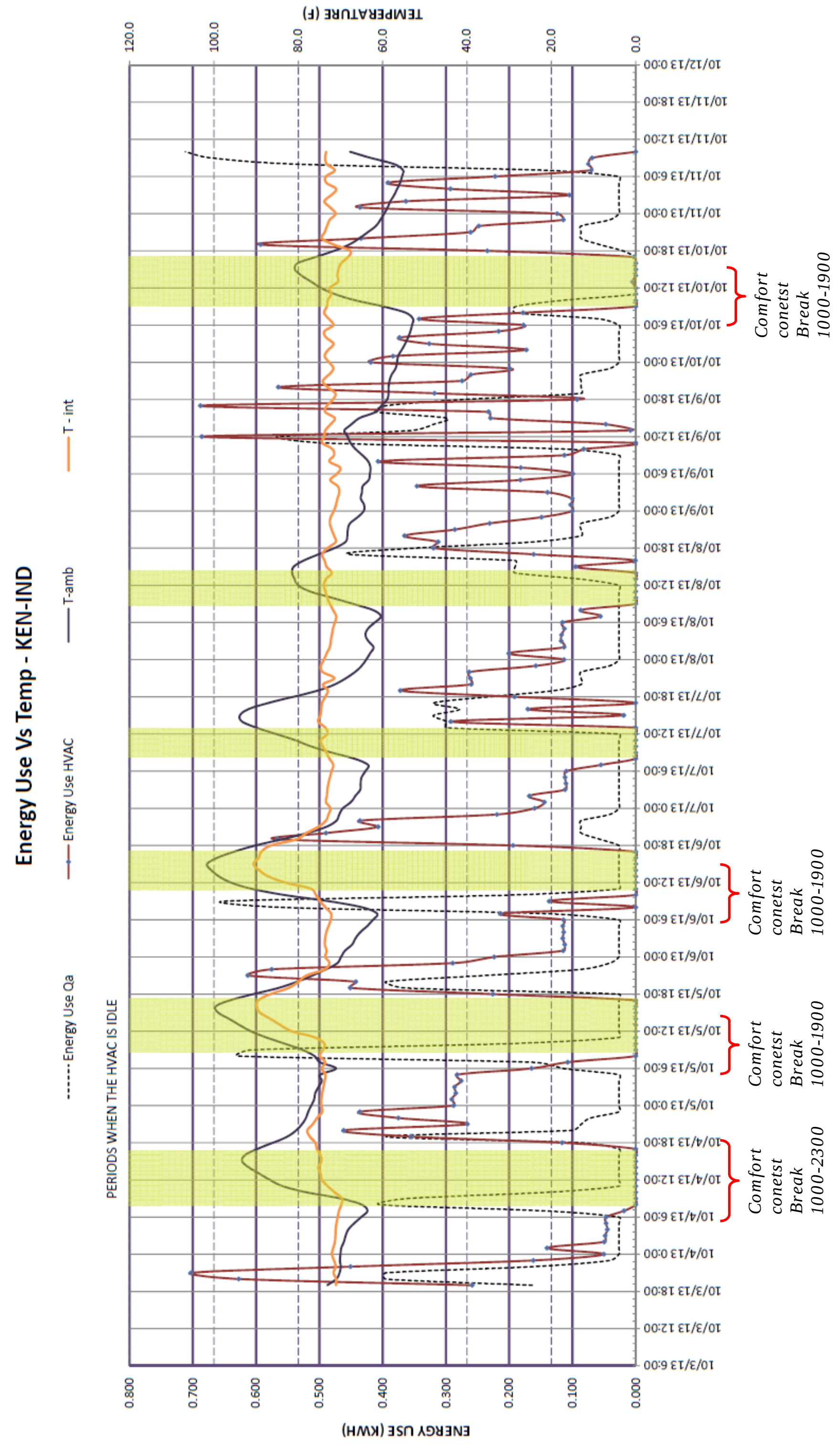


Figure 18 Time Series -Energy Use vs Temperature - Example Group A

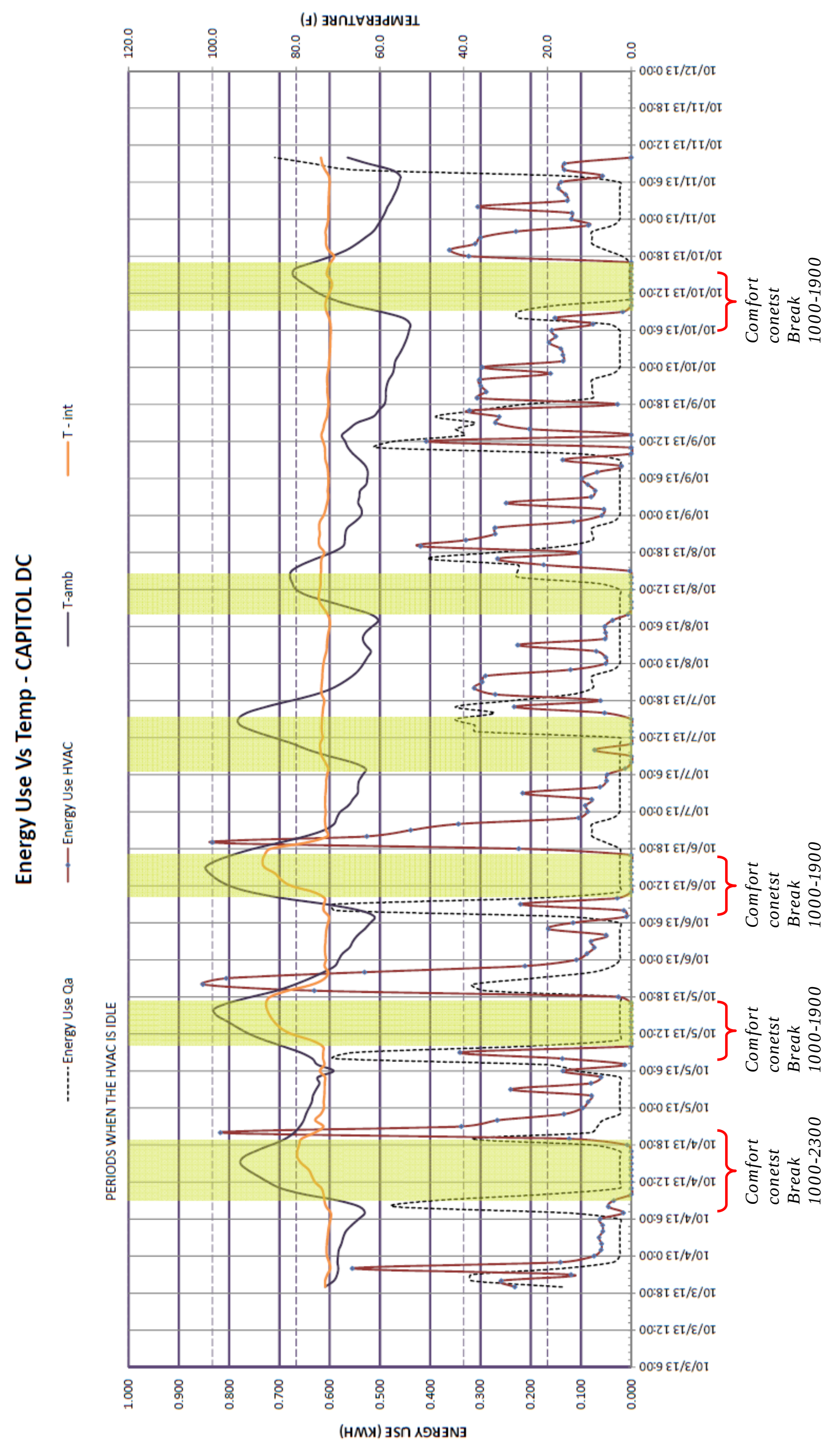


Figure 19 Time Series -Energy Use vs Temperature - Example Group B

The next step following the observations from Figures 16, 17, 18 and 19, was to repeat the regression of variable X1 with outside temperature and excluding the null readings, and to be able to associate the two distinct clusters with components within the comfort system of the houses.

Also based on the observation above it was clear that the expected form of the steady state inverse model will be of for heating and be similar to Figure 20. [Kreider et al.2010]

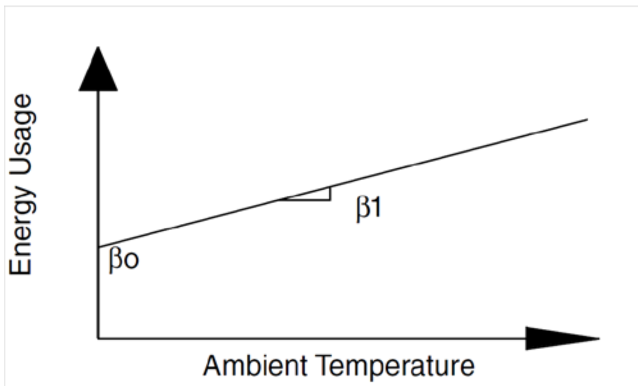


Figure 20: Steady State Inverse model - 2P

Such a model will have the equation of the form.

$$E_{period} = \beta_0 \pm \beta_1 T$$

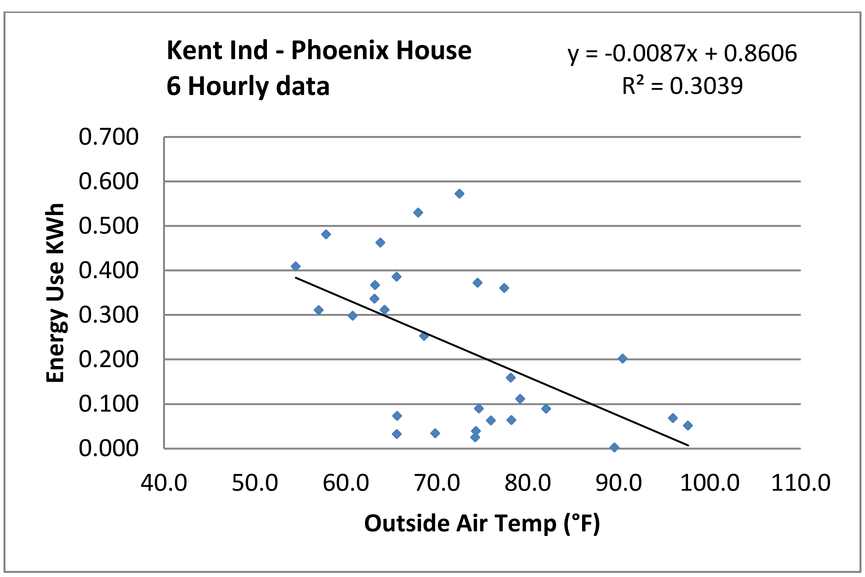


Figure 21 Group A - Example HVAC energy use (predominantly heating).

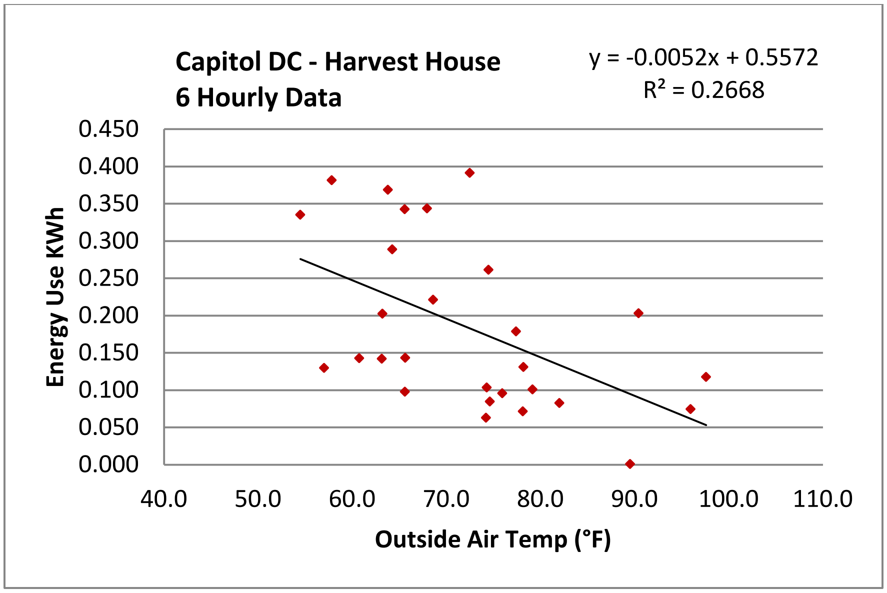


Figure 22. Group B - Example HVAC energy use (predominantly heating)

As expected, both groups show a predominantly heating pattern, however there are several flaws with this model.

1. The data in its current form cannot identify those two occasions when cooling was required.
2. There is also little explanation for the previously established clusters. That is the equation cannot distinguish between a base (HVAC) energy signature and when the primary components are active.
3. Above all the low R^2 implies that there is little utility for this model as a predictor. Based on the observations above and from Figure 18 and 19 it is possible to identify and distinguish the heating and cooling times and break down the HVAC from a 2 point model to a 3 point change point model we can capture the change point. The new model will be of the expected form:

$$E_{period} = \beta_0 \pm \beta_1(T - \beta_2)^+$$

Here positive β_1 will reflect cooling and will have an expected graph form as shown in Figure 23.

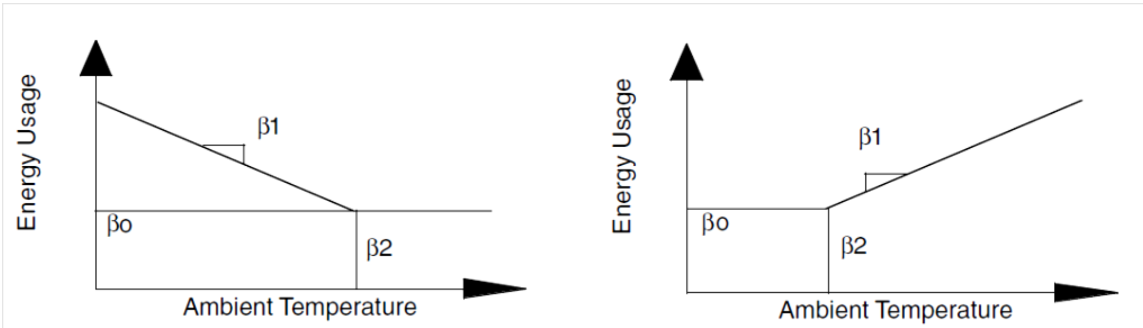


Figure 23: Steady State Inverse model - 3 Parameter change point.

Following are the two examples from group A and B with scatterplot of the separated cooling and heating data based on observations from Figures 18, 19 and 20, 21. After discounting the null readings and separating the two heating/cooling values there were not enough data points for a useful plotting and therefore, I had to switch back to the hourly data format.

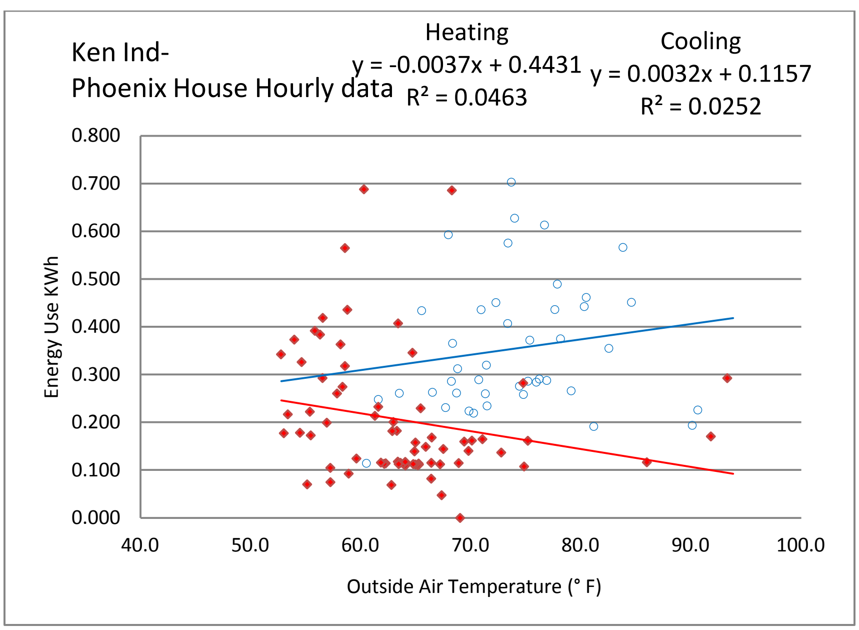


Figure 24: SS- Inverse model (heating and cooling separated) - example Group A

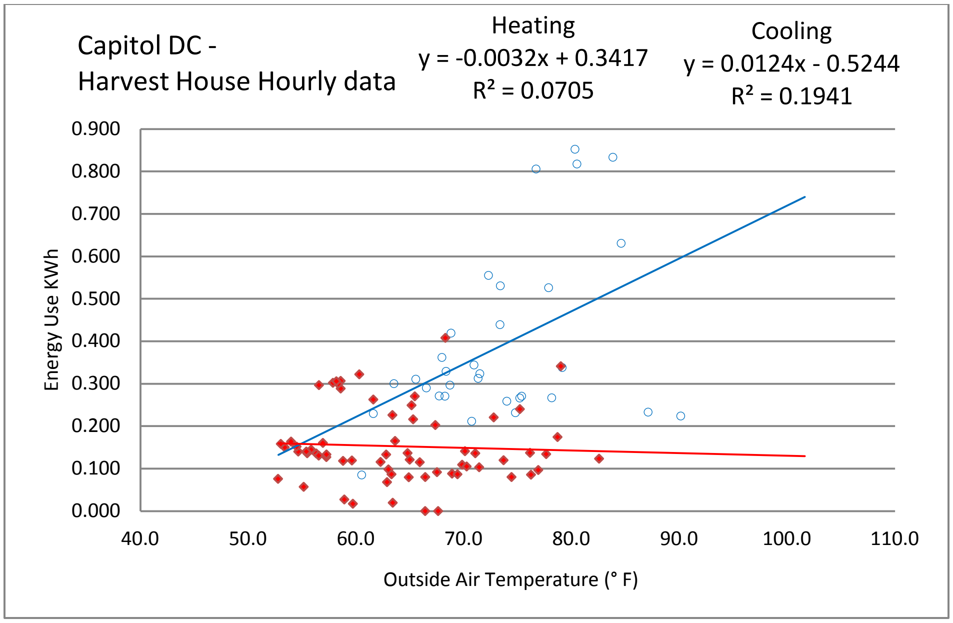


Figure 25: SS- Inverse model (heating and cooling separated) - example Group B

Figures 24 and 25, we note that,

1. As expected the hourly data in both examples is extremely noisy. In all four equations the R^2 is small; therefore the regression equation cannot be used to forecast energy use with certainty.
2. The models at its current state cannot address dynamic or transient effects related to thermal mass of the building. Especially, considering the fact that, for the competition, the homes though small in volume and surface area had a high thermal mass with many homes opting for phase change materials etc.
3. So far the model has only accounted for temperature as the predictor variable. It does not take into account humidity, solar radiation.
4. The choice of model seems to be ineffective in capturing the trends due to lack of a large outside air temperature range, in other words the temperature swings were not substantial.

5. This model is somewhat similar to what is commonly understood as a 3P change point steady-state inverse model [Kreider et al. 2010]. This model differs from the common form in that this is an energy signature of only the HVAC related energy use and does not have the baseline energy use built in. However, the baseline loads (Non HVAC - end use) have already been segregated in chapter 5 and the fact that the baseline loads are predominantly independent of the predictor variable (temperature). All the non HVAC equipment end-use can be added to the model as baseline loads through a set of constrains equation with a slope '0.00'. Such that

$$y = C + 0.00x \text{ s.t, } C = \{X_2\text{: X9}\}$$

As an example, consider the house from Group B, although an accurate way to approach this constraint optimization will be to use the discrete minimum and maximum baseline signatures to derive a range of energy use values, for the sake of discussion I have the weighted average of the non HVAC end-use as a baseline where $y = 0.105 + 0.00x$

This now becomes a linear optimization with three equations the baseline, heating and cooling. Please note that the heating and cooling equations are not the reliable in their current state. However for the sake of discussion - the equations can be solved as

$$y_{base} = 0.105 + 0.00x + K$$

$$y_{heat} = 0.3502 - 0.0033x$$

$$y_{cool} = -0.4457 + 0.0108x$$

Where, $51.2 < x < 74.3$ and 'x' represents the positive T s.t $x = |T - \beta_2|$ where β_2 is the 'change point' temperature values where there is no heating or cooling energy consumption.

Modifying the Steady State Inverse Model.

As noticed in both the cases above, the inverse model is inept in capturing the time constant and the thermal mass of the buildings; thermal mass is an added complexity - a parameter other than temperature that effect the energy performance of the HVAC. The behavior of this thermal mass as a temporary capacitance contributes to the time lag between heat added and being removed from the building which is a parameter for the instantaneous transfer of heat. In this context, to estimate these two variables from the temperature parameter we need to first find the difference between the outside and inside temperatures. From the time series data of outside air temperature and the internal temperature we can derive the ΔT associated with each energy reading.

delta T	Quality T	KEN COOL	KEN HEAT
3.8	3.8	0.258	
3.0	3.0	0.628	
2.1	2.1	0.703	
1.2	1.2	0.451	
1.4	-1.4		0.162
2.0	-2.0		
1.9	-1.9		0.140
2.1	-2.1		
2.4	-2.4		
3.0	-3.0		
4.2	-4.2		
5.6	-5.6		
6.8	-6.8		
4.9	-4.9		
0.3	0.3		
6.7	6.7		
10.7	10.7		
12.3	12.3		
14.5	14.5		
16.4	16.4		
18.8	18.8		
17.9	17.9		
14.2	14.2		
10.0	10.0		0.117
5.3	5.3	0.355	
2.7	2.7	0.462	
3.4	3.4	0.436	
2.4	2.4	0.288	
1.7	1.7	0.291	
1.7	1.7	0.284	
1.2	1.2	0.286	
0.7	0.7	0.276	
1.2	1.2		0.282
3.3	-3.3		0.165
1.3	1.3		0.108
1.3	1.3		
4.8	4.8		
9.4	9.4		
11.5	11.5		
9.7	9.7		
9.7	9.7		
9.8	9.8		
9.9	9.9		
9.8	9.8		
6.7	6.7		
4.1	4.1	0.226	
2.3	2.3	0.451	
0.4	0.4	0.443	
1.3	-1.3	0.613	
0.3	-0.3	0.576	
1.9	-1.9	0.289	
3.7	-3.7	0.224	
4.4	-4.4		0.115
19.4	-19.4		0.178
13.5	-13.5		0.000
6.6	-6.6		0.000
1.0	-1.0		0.000
2.1	2.1		0.000
6.3	6.3		0.005
8.5	8.5		0.000
10.3	10.3		0.000
10.3	10.3		0.000
7.7	7.7		0.003
3.8	3.8	0.235	
3.6	-3.6	0.593	
8.8	-8.8	0.434	
10.2	-10.2	0.261	
11.6	-11.6	0.248	
12.0	-12.0	0.114	
11.5	-11.5		0.124
13.6	-13.6		0.436
15.6	-15.6		0.363
14.9	-14.9		0.105
14.5	-14.5		0.293
17.5	-17.5		0.392
18.0	-18.0		0.222
16.2	-16.2		0.070
16.0	-16.0		0.075
10.8	-10.8		0.069
5.6	-5.6		0.000

Table 15: X1 vs ΔT (OAT-IAT) with Heat Map - Abridged

We note clearly, from the above table that there is a definite thermal mass effect the orange response variable is HVAC energy used for cooling which is trailing the peak outside air temperature. The blank cells are the null readings when the comfort system was not in effect or the ΔT wasn't significant enough to trigger heating.

To calculate the time constant for the buildings, I calculated the heat flux value UA (in our case this is in (KW/ft^2) values for the contestants based on the HVAC energy use - using the equations.

$E_{hvac} = UA(\Delta T) \quad OR \quad UA = \frac{E_{hvac}}{\Delta T}$

Also Time Constant can be found as

$\frac{\delta \Delta T}{\delta t} + \frac{1}{\tau}(\Delta T) = 0$ With $\tau = \frac{\rho . C_p . V}{h . A}$

			Average UA	Area sq ft
GROUP A	Ken Ind	Phoenix House	0.0987	900
	Middlebury	Insite	0.0993	925
	Misso.S&T	Chameleon	0.1458	987
	Stanford	Start Home	0.0920	988
	Stevens	Eco Habit	0.0337	918
GROUP B	Alberta	Borealis	0.0959	915
	Capitol DC	Harvest	0.0616	780
	Las Vegas	Desert Sol	0.1671	754
	N Carolina	Urban Eden	0.0639	825
	Ontario	Echo	0.1599	942
	Univ. So Cal	Fluxhome	0.4316	900
	Sci Arc/ Caltec	Dale	0.0741	
GROUP C	Santa Clara	Radiant House	0.1412	844
	ASU/UNM	Shade	0.1104	851

Table 16: Calculated thermal mass and Time constant values.

6.2 Thermal Networks

Discussed briefly in Section 3.4 - thermal network study was primarily done to determine the capacitance/ time constant for the houses and then compare it with the results from the modified inverse model study to verify the effectiveness of the model. As discussed earlier a limitation of the steady state analysis is its inability to deduce the thermal mass and the time constant as parameters. The result of both the studies and establish a numerical value to time constant as a correlation parameters and its effect on the response variables.

The study was done using a single node thermal network (Figure 8) diagram and equation in section 3.4 and the following equations were used:

$$\dot{T}_i = \left(T_a \dot{-} T_i\right)\alpha + \dot{Q}_{int}\,\beta \pm \dot{E}_{ac}\,\gamma$$

$\alpha = \dfrac{1}{\tau}$ *where* τ *is the time constant*

$\beta = \dfrac{1}{C}$ *where* C *is the capacitance*

$\gamma = Efficiency\ /Capacitance$

TIME	T_a	T_i	Q_a	E_{ac}	$T_a - T_i$	$\dot{E}_{ac}$	$\dot{T}_i$	$(T_a \dot{-} T_i)$	$\dot{Q}_a$
10/3/2013 19:00	73.1	71.0	0.164	0.258	2.1	--	--		--
10/3/2013 20:00	71.0	71.0	0.395	0.628	0.0	0.369	0.0	-2.1	0.231
10/3/2013 21:00	70.2	71.6	0.395	0.703	-1.4	0.076	0.6	-1.4	0.000
10/3/2013 22:00	69.9	71.1	0.164	0.451	-1.2	-0.252	-0.5	0.2	-0.231
10/3/2013 23:00	70.1	71.5	0.042	0.162	-1.4	-0.289	0.4	-0.2	-0.122
Abridged									
10/11/2013 6:00	55.4	73.4	0.027	0.222	-18.0	-0.170	0.1	-0.5	0.000
10/11/2013 7:00	55.2	71.3	0.142	0.070	-16.2	-0.152	-2.1	1.8	0.115
10/11/2013 8:00	57.3	73.2	0.537	0.075	-16.0	0.005	1.9	0.2	0.395
10/11/2013 9:00	62.8	73.6	0.670	0.069	-10.8	-0.006	0.4	5.2	0.134
10/11/2013 10:00	67.7	73.4	0.712	0.000	-5.6	-0.069	-0.2	5.1	0.041

Table 17 Abridged Thermal network regression table for Group A house - Ken Ind.

Based on the above networked regression, the following coefficients were predicted and plotted against the residuals. Once again in this study the R^2 is a very small number therefore, it is advised to look at coefficient of variance (CV). Since this is a multi-parameter model, the CV was calculated as the ratio of the Root Mean Square Error and the mean of the dependant variable.

Therefore the use of this equation to predict any accurate variables cannot be verified.

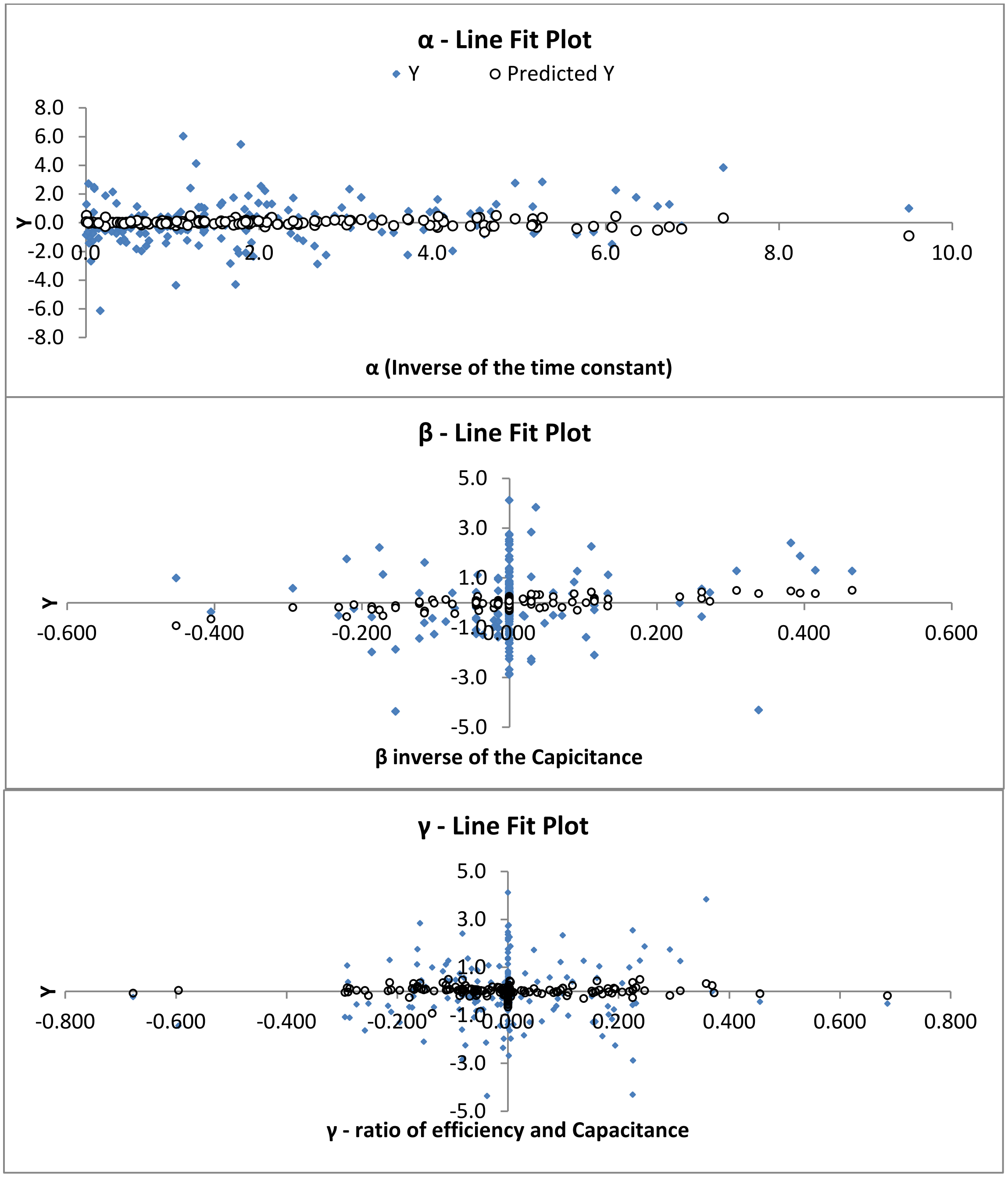


Figure 26: Line Fit plot of the equation variables.

Similar analysis of the group B revealed a small value for R^2. Despite the low utility of the equation predicted vs measured inside temperature plot is generated as an example for the sake of completion for this chapter of this study in hopes to find a better data in future and be able to use this as a template. The graph below shows the time series of the measured vs the equation based predicted temperatures.

Figure 27 clearly indicates that the modeled temperature calculated with the equation vs measured temperature are a good fit and therefore can be used to calculate the time constants.

Based on the modeled equation the coefficient $\alpha = 1/\tau$ or $\tau = 1/\alpha$. Table 18 shows the derived Time Constants.

TEAM	R^2	α	β	γ	τ
KEN.IND	0.55	0.16	-24.05	-0.77	6.25
MIDDLEBURY	0.75	0.13	-35.4	-0.74	7.7
MISS.S&T	0.6	0.08	-20.8	-1.05	12.5
STANFORD	0.45	0.02	-49.2	-4.66	50
STEVENS	0.48	0.09	-40.2	-5.91	11.1
ALBERTA	0.05	0.04	-0.345	-0.11	24
CAPITOL DC	0.79	0.12	-0.001	-0.00	8.3
LAS VEGAS	0.75	0.31	-39.5	-1.8	3.22
N. CAROLINA	0.6	0.12	0.38	-4.7	8.2
ONTARIO	0.27	0.03	-25.33	-2.4	40
SO. CAL.	0.33	0.21	3.5	-0.19	5
SCI.ARC/ CAL	0.45	0.14	22.6	-3.2	7.2
SANTA CLARA	0.34	0.06	1.3	-2.45	3
ASU/UNM	0.49	0.11	47.11	-3.7	8.9

Table 18. Time Constants based on the thermal network equations.

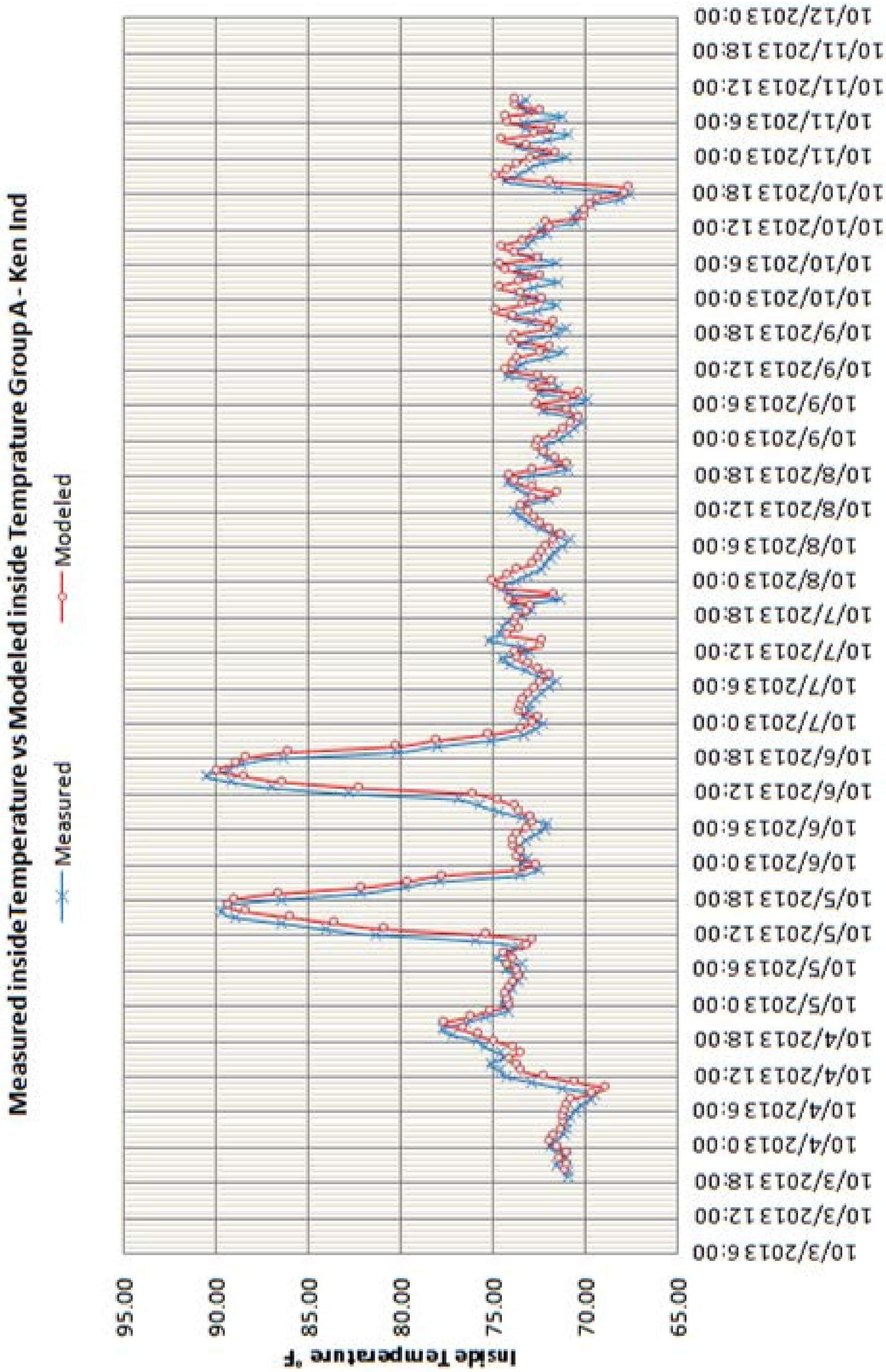


Figure 27: Modeled Temperature vs Measured Temperature.

6.3 Discussion

In Section 6.1, several efforts to modify the steady state inverse model to make it more accurate were tried by adding layers of complexity. These involved separating heating and cooling energy end-use based on sign of ΔT and referencing it with the schedule of operation, by removing outliers and null readings, and by adding thermal mass. Observations based on the result of the various iterations of the modified steady state inverse model have clearly indicated a poor coefficient of determination of the regression model, and an inconclusive coefficient of variation in some cases. The data is noisy and has large squared deviations from the regression fit model.

Since mean as statistic is more prone to be influenced by such noisy readings and outliers, perhaps using a statistic other than the mean that is not affected by the outliers and the noise should be considered for further investigation of the segregated heating and cooling data, and to establish any model equation for energy end use.

Figures 28 and 29 - box plots compare the heating and cooling electric energy end-use data. This data has been segregated based on the operation schedule and the temperature responses on the Median based on the occupied and the unoccupied whole building energy use. As expected, the box plots reveal that despite outlier removal the data for all the teams is right skewed for the heating component and moderately skewed to almost normal for the cooling component. The heating energy use is nearly 0.4-0.6 times as the cooling end use. However, the schedule heating time (negative ΔT) is nearly 3 times more. Therefore, it can be said that the efficiency of the heating systems is definitely greater than the cooling systems in all the teams. It is observed that on average among all the teams, teams in Group B have better energy performance numbers that Group A for Heating. Group B are the teams with Solar Thermal + Auxiliary electric coil being used through radiant heating distribution.

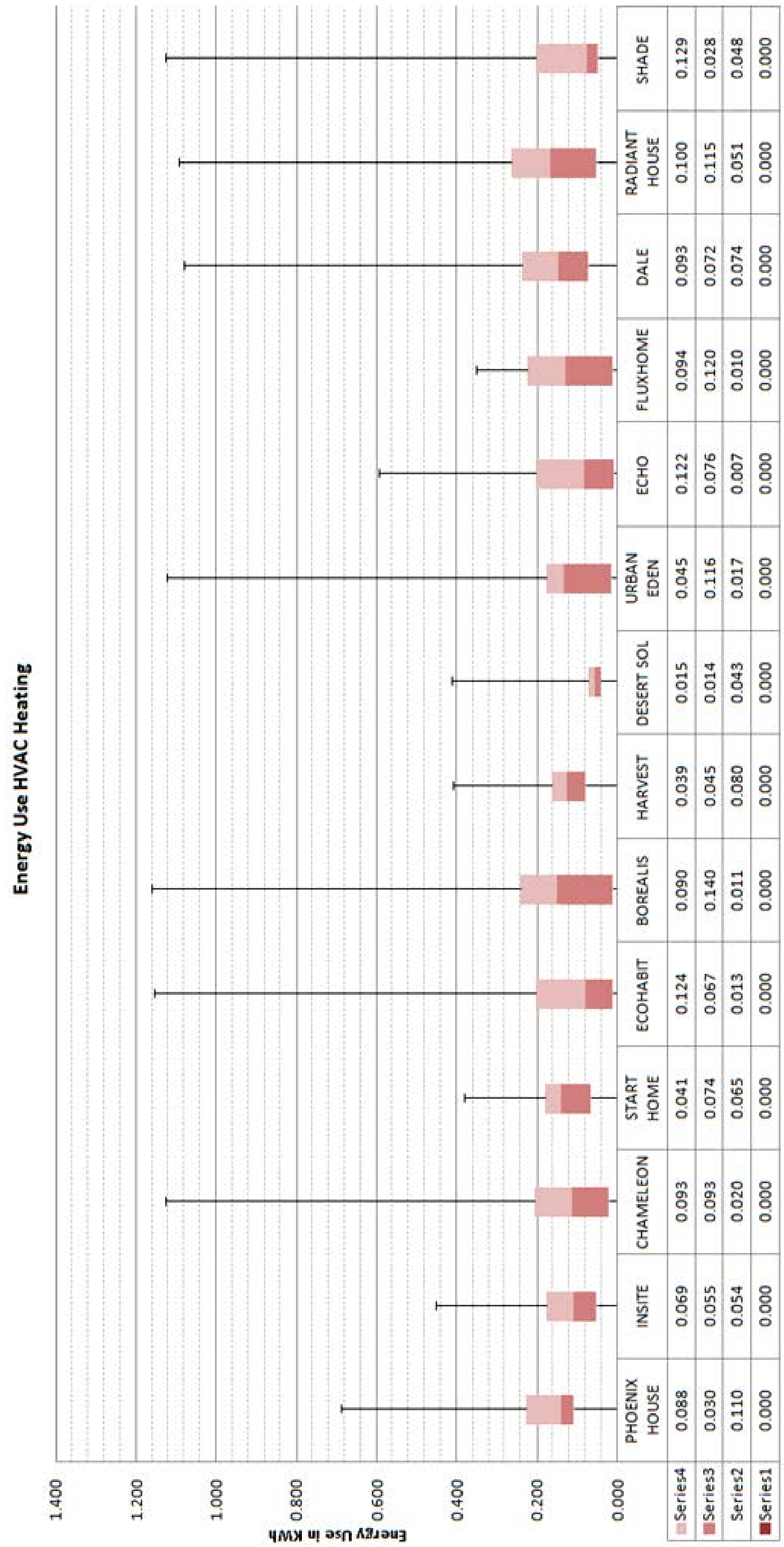


Figure 28: Box Plot Heating Energy Use.

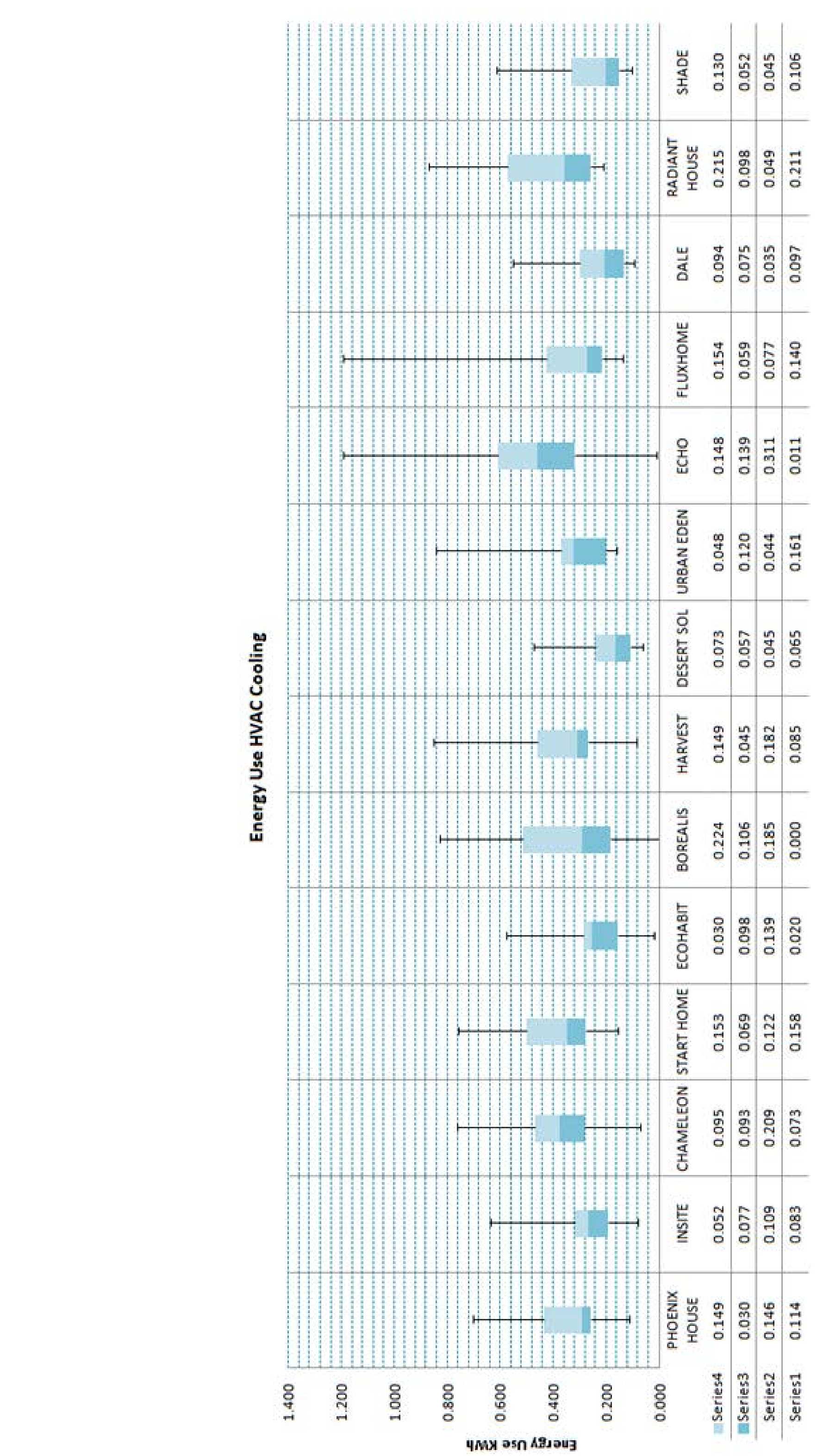


Figure 29 Box Plot Cooling Energy use.

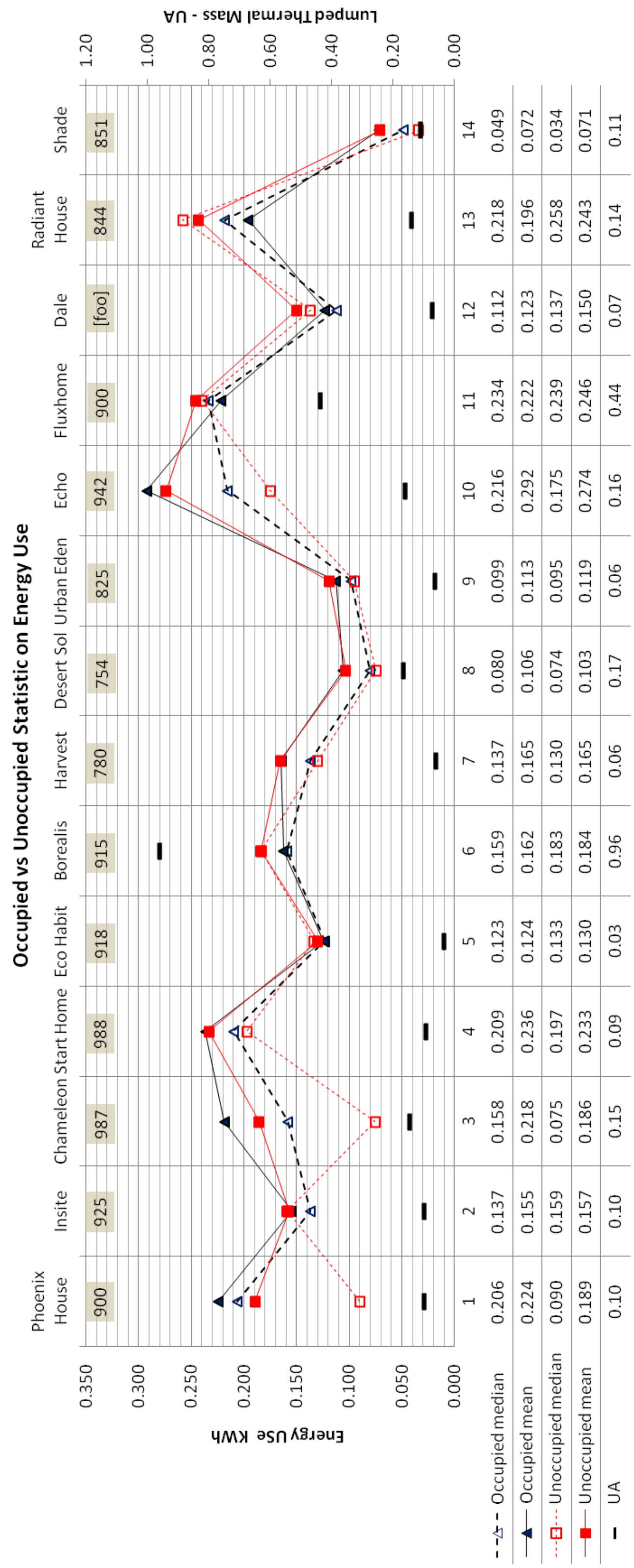
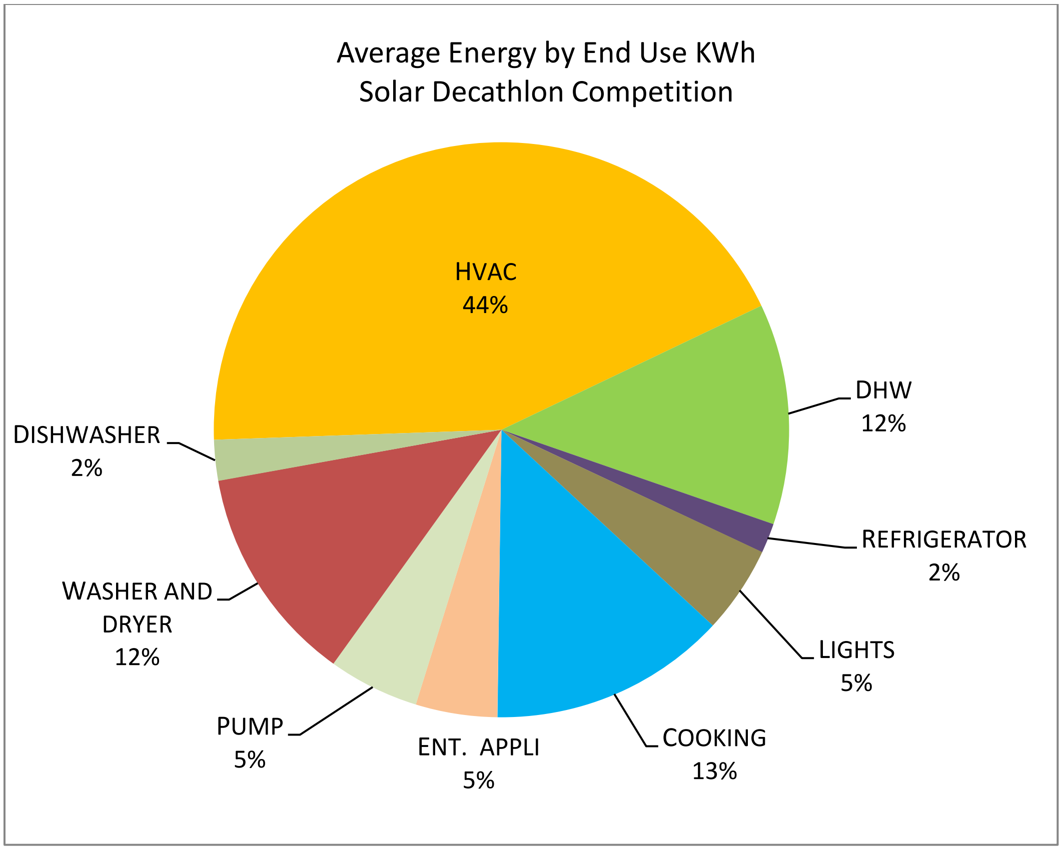


Figure 30: Occupied vs Unoccupied Energy Use.

Table 19 compares in detail the median and the inter-quartile ranges of heating and cooling and also compares these with the medians of the occupied and the unoccupied electric energy.

Team	Heating		Cooling		Occupied	Unoccupied
(all values in KWh)	Median	Inter-Quartile Range	Median	Inter-Quartile Range	Median	Median
A						
Ken-Ind	0.140	0.11-0.23	0.290	0.26-0.44	0.206	0.090
Middlebury	0.110	0.05-0.18	0.259	0.19-0.31	0.137	0.159
Miss.S&T	0.113	0.02-0.2	0.379	0.28-0.47	0.158	0.075
Stanford	0.139	0.06-0.18	0.348	0.28-0.50	0.209	0.197
Stevens	0.080	0.01-0.2	0.257	0.16-0.28	0.123	0.133
B						
Alberta	0.151	0.01-0.24	0.291	0.19-0.51	0.159	0.183
Capitol DC	0.125	0.08-0.16	0.312	0.27-0.46	0.137	0.130
Las Vegas	0.060	0.05-0.08	0.157	0.10-0.23	0.080	0.074
N. Carolina	0.134	0.02-0.18	0.321	0.20-0.37	0.099	0.095
Ontario	0.083	0.00-0.20	0.452	0.32-0.60	0.216	0.175
U. So- Cal	0.130	0.01-0.23	0.276	0.22-43	0.234	0.239
SciArc	0.146	0.07-0.24	0.207	0.13-0.30	0.112	0.137
C						
Santa Clara	0.166	0.05-0.26	0.358	0.26-0.57	0.218	0.258
ASU/ UNM	0.076	0.05-0.20	0.201	0.15-0.33	0.049	0.034

Table 19: Median and Inter-quartile Data.



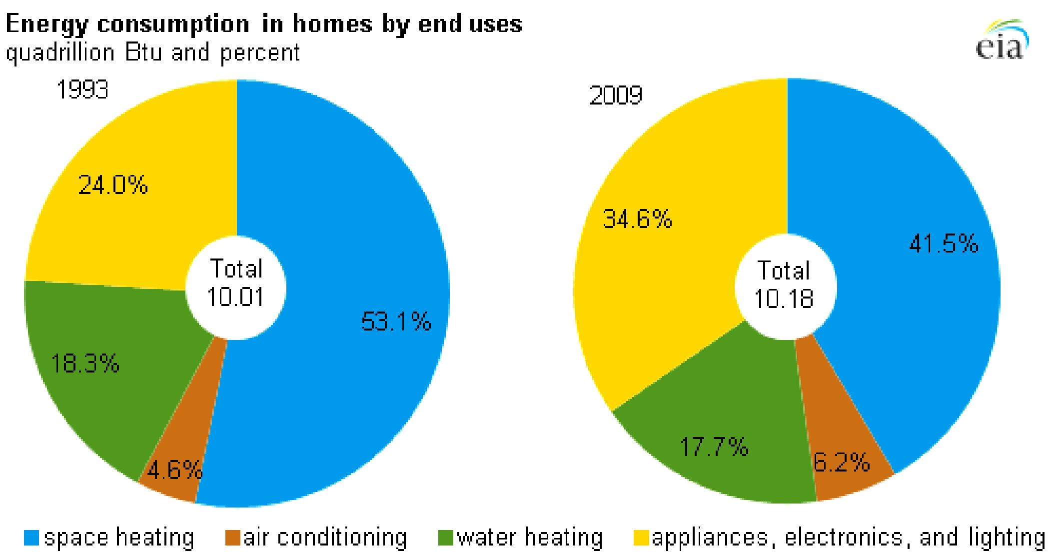


Figure 31 : Comparison Energy use percentage by End use.

The following can be deduced from Table 18,19 nd appendix A.

1. Based on limited data available from the contestants, that could be verified from the drawings and the specifications, on an average the thermal insulation in the ultra efficient house seems to be higher than the traditional homes in Irvine, California. On an average the Roof values R values were 45, walls were 30 and the floor were 30. Typically the houses opted for 30-40 percent window wall ratio.
2. Based on the segregated energy - end-use data the electric energy use for HVAC - heating and cooling combined accounted for 44 % of the total energy use. This is similar to the almost 48% from the 2009 data where the heating is through a non -electric energy source. For the prototype houses in Irvine the cooling energy use based n median was 0.1-0.6 KWh - nearly twice as much as the heating energy use 0.0-0.26 KWh despite the time series data that suggested that heating was required nearly thrice as much as cooling.
3. From figures 28 and 29 it ca n be inferred that the heating data fro teams in group B is more consistent with smaller inter-quartile ranges also verified from the time series energy signature and inside temperature graphs. On an average group B with solar thermal radiant - heating systems perform marginally better than the heat pump based hybrid systems.
4. The inter-quartile ranges for teams in group A and B are nearly equally spread and are on an average 30 - 40 % of the entire data set. Therefore the cooling data is particularly noisy and perhaps there are other parameters affecting the data thereby undermining the influence of temperature. A closer inspection of the time-series graph and the operations schedule reveal regularly occurring cooling peak demand between 19:00 -22:00 hrs soon after the visiting hours get over. This also coincides with other activities that may require frequent breach of

envelope - increased infiltration. This could explain the larger inter-quartile range for cooling peak demand but without mapping humidity this it cannot be concluded with any certainty.

5. It is also observed that despite a good fit for the thermal network equation due to poor coefficient of determination and large standard errors and variation the time constants derived from the equation cannot be entirely reliable. However a trend is observed that the whole house lumped time constant range from 6-9 hours which is quite reasonable and can be expected.

6. As expected the Domestic water heating was the next main energy consumer end use tied with washer dryer. Notice that the solar decathlon does not have a gravity fed water supply system, therefore in all cases there is an upstream pump. When the pump energy use is accounted and added to the water / dryer and the domestic water heating the end use assume 16-18% energy use each. The water heating data from RECS data in Appendix B and the data in figure 31 are energy use by non-electric water heating with a combustible fuel source and should not be compared with the percentage numbers above.

7. As expected a continuation of the trend from 1993-2009 data the electric energy consumption from the electronic appliances and lighting is on the rise. From 34 % as recorded in 2009 it is up to almost 44 % (this includes the 13 % cooking).

Common to all the points above is the fact that the processed data throughout the study cannot rule out the significance of the operation schedule, which has overtly influenced the study and constrained the process of estimation. On the flipside, the schedule does help in providing insight as to why a certain energy use trend was observed. Therefore, with this mixed bag of findings I will like to conclude with the following summary.

CHAPTER 7

SUMMARY AND FUTURE WORK

7.1 Summary

The primary objective of this study, to investigate the electric energy consumption by end use and analysis of the electric energy use of the HVAC system for the prototype homes at Solar Decathlon. Towards its fulfillment, analysis through schedule bifurcation, segregation of end use, separation of heating & cooling loads, separation of occupied and unoccupied usage and thermal network have been examined. The conclusion of this study and processed data have been discussed in 6.3 and have alluded to several expected and several surprise results.

Without getting into detailed re-iteration of the analysis here is a brief description of critical observations specific to electric energy end-use for the 14 prototypes.

1. That on an average HVAC based electric energy use contributed to 38-48% of the electric energy use in the ultra efficient home, followed by 15-25% electric energy use for the domestic hot water, 15-25% on electricity based cooking, 18-22% on the washer and dryer. The lighting and appliances contributed 8-12% each. Surprisingly the refrigerator was found to be a small contributor between 2-5% of the total electric energy consumption.
2. It was observed that during the competition at Irvine, the primary part of HVAC engaged over a larger period of the comfort contest was the heating system, however it is the cooling system that is the higher electric energy consumer.
3. Using median and inter-quartile range as statistic it was observed that overall the heating energy use ranged between 0.00-0.26 KWh compared to 0.10 - 0.60 KWh for the cooling systems.

4. The means energy use for neither heating not cooling for either cooling or heating are insufficient to conclude which type of system technology outperformed the other in Groups A and B. However, it is observed that in the heating department the Group B teams with solar thermal assisted radiant heating has more consistent and marginally better performance data than Group A with an air based distribution system. The average of the median energy use scores from all the teams in group 'B' is 0.11 KWh as compared with 0.18 KWh for teams in 'A'.
5. Surprisingly the energy use for lighting and the refrigerator is greatly reduced and perhaps the lighting (due to LED) and refrigerators (due to efficient compressors) in the refrigerators are two end-uses that have seen drastic improvement over the national averages based on RECS data [appendix B].

While the quantitative analysis, its key findings have been presented above and in greater detail in the preceding sections and meet the preset objective of the study, the overall accuracy, efficacy and quality of the process is subjective and requires a deeper and critical evaluation of the holistic process that includes data collection, contest rules , overall purpose and intent of the competition. Following is a commentary on a few aspects of the competition that influence the quality and efficacy of this study and which are beyond the scope of mechanics of the quantitative analysis.

As discussed earlier the research was based on the data available from DOE and used this data with faith on its accuracy. The outside and indoor dry bulb temperature was used as a predictor variables and energy use as the dependant variable. Comfort systems do not only depend on the temperature, humidity is equally important, and while the competition does stipulate a temperature range of 72-76 F and under 60% humidity, the method of collection of this data is biased and suited only to the teams with conventional air based cooling and heating systems that rely on these traditional parameters for their control systems meant for convection based comfort delivery. Teams with newer efficient technologies with a radiant comfort delivery system -that is more effective in providing thermal comfort are at a disadvantage when they have to rely on dry bulb temperature and humidity as control parameters.

The radiant technology equivalent to testing efficiency for providing human comfort will be *mean radiant temperature (MRT).* The probe type sensors used to measure the internal dry bulb temperature and humidity are incapable of measuring the MRT and are therefore promote unfair bias towards use of certain kind of technology.

Also it can be said that the nature of the competition itself, sabotages the intent behind the Ultra-efficient home and the whole building design approach, the houses are designed for different climate zones that are representative of the native climates that the contestants, the houses are displaced from their natural designed environment to be tested in a dissimilar environment.

Due to the complete mismatch of the design setting and the test setting, no quantitative evaluation can be a true representation of the performance of the design and technology and therefore any judgment on the performance based on such a quantitative data will be completely inaccurate and unreliable.

Therefore, based on the quality and nature of the available data both in terms of readings and the time period, limited use of parameters during the study, repeated poor coefficient of determination during the analysis and the stipulated time frame for the master's thesis report I conclude that despite some expected result the findings cannot be entirely accepted without further analysis. While the study does satisfactorily breaks down the key components and identifies a process towards achieving its primary objective, the analysis suffers from the quality and accuracy of data.

7.2 Future Work

Indicated earlier, the larger intention behind this study is to support the proponents of the whole building design approach and to add to the existing data that help further the knowledge and insight to accurately steer the residential sector energy consumption through informing existing survey based indicators and indices maintained by the department of energy. The effectiveness of such studies is not instantaneous and should not be evaluated in isolation but rather as a purposely researched segment for a larger cumulative research.

In its current form the study could only scrap the surface of energy performance with relatively simplistic techniques. A deeper dive into more evaluation techniques is necessary; equally necessary is collection of reliable and accurate data with a longer and consistent time duration.

The study for all the prototypes should also be conducted if possible in their native design environments through the seasonal changes. A comparative analysis that examines the year on year performance of these systems will be truly meaningful addition to the larger intent behind such studies and help in long term policy making.

Finally, perhaps such studies and an year on year analysis can be the incentive for the Solar Decathlon competition to evolve into a more mature international entity - one that is not limited to a month long contest, rather that allows teams to compete with real-time data collected and analyzed month after month and allow continuous iterations to the design of these buildings in their native environments.

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WEBSITE

Team Data - Solar Decathlon (2013) - www.solardecathlon.gov

Department of Energy - energy.gov

Residential Energy Consumption Survey (RECS) - www.eia.gov

APPENDIX A

DATA FROM THE CONTEST AND CONTESTANTS

A.1 Competition Parameters and the Measured Contests.

Solar Decathlon, true to its name, has ten equally weighted contests that are judged and form the premise for the teams to design, engineer and construct these houses. The contests are categorized as either juried contest or a monitored or measured -contests

The following is a brief account each of these contests:

1. **Architecture** is a juried contest where the teams are required to design and build attractive, high-performance houses that integrate solar and energy efficiency technologies seamlessly into the design. Typically they are judged on programming, scale and proportions of architectural elements and the holistic design approach.
2. **Market Appeal** is a juried contest where the jury, composed of professionals from the homebuilding industry, evaluates the responsiveness of the house design to the characteristics and requirements of the target client chosen by the teams to design their prototype home for. They are concerned with the issues of marketability, build-ability and livability.
3. **Engineering** is a juried contest where the functionality, efficiency, reliability and overall innovation of the active systems of the prototype house that help in reducing the overall energy consumption.
4. **Communications** is a juried contest where the format, the quality and the consistency of the message, vision and experience of the house is communicated to diverse group of people of all abilities and judged based on their opinion of the communication.

5. **Affordability** all prototype houses are expected to be affordable and to encourage uniformity and fairness and cap of $250,000 is placed as the budget ceiling for design and construction of the house. Exceptions that cross the limit are severely penalized.
6. **Comfort Zone** this is a *measured contest* where the temperature and humidity is measured inside the house and points are awarded based on the ability of the prototype house to maintain a narrow band of temperature range between 71°F (22.2°C) and 76°F (24.4°C) and maintain humidity levels under 60%.
7. **Hot Water this** is a *measured contest* to deliver 15 gallons (56.8 l) of hot water (110°F/43.3°C) in 10 minutes or less.
8. **Appliance Contest** is a measured contest designed to mimic the appliance use of an average U.S. home The following data is recorded for the purpose of the contest:
    - Maintaining the refrigerator temperature between 34°F (1.11°C) and 40°F (4.44°C)
    - Keeping the freezer temperature between -20°F (-28.9°C) and 5°F (-1.5°C)
    - Washing a load of laundry within a specified period of time.
    - Returning a load of laundry to a total weight less than or equal to the load's total weight before washing using active or passive drying methods
    - Running the dishwasher through a complete, uninterrupted cycle, at some point during which a temperature sensor placed in the dishwasher has to reach 120°F (48.9°C).
9. **Home Entertainment Contest** gauges how well does it accommodate the pleasures of living, such as sharing meals with friends and family, watching

movies in a home theater, and checking social media? How well does it accommodate a small home office for a telecommuter? and includes :

- Keeping all interior and exterior house lights on during specified periods of time
- Operating a television and computer during specified time periods
- Simulating cooking by using a kitchen appliance to vaporize 5 pounds (80 oz or 2.268 kg) of water within a specified period of time.

10. **Energy Balance Contest** each team house is equipped with a bidirectional utility meter that enables competition organizers to measure the net energy a house produces or consumes over the course of the competition.

In the end, the prototypes are expected to demonstrate that they are affordable, attractive, easy to live in, and maintains comfortable and healthy indoor environmental conditions. How they supply energy to household appliances for cooking, cleaning and entertainment is another criterion, as is the issue of whether they provide adequate hot water and if they produce as much or more energy than they consume.

A.2 Classification of Methods for Thermal Analysis of Buildings [Kreider et al. 2010]

Method	Forward	Inverse	Hybrid	Comments:
		Steady State Methods		
Simple linear regression		X		One dependent parameter, one independent parameter. May have slope and y-intercept.
Multiple linear regression		X	X	One dependent parameter, multiple independent parameters.
Modified degree-day method	X			Based on fixed reference temperature of 65°F.
Variable base degree-day method	X			Variable reference temperatures.
ASHRAE bin method and inverse bin method	X	X	X	Hours in temperature bin times load for that bin.
Change point models: 3-parameter (PRISM CO, HO), 4-parameter, 5-parameter (PRISM HC).		X	X	Uses daily or monthly utility billing data and average period temperatures.
ASHRAE TC 4.7 modified bin method	X		X	Modified bin method with cooling load factors.
		Dynamic Methods		
Thermal network (Sonderegger, 1977)	X	X	X	Uses equivalent thermal parameters (inverse mode).
Response factors (Stephenson and Mitalas, 1967)	X			Tabulated or as used in simulation programs.
Fourier Analysis (Shurcliff, 1984; Dhar, 1995)	X	X	X	Frequency domain analysis convertible to time domain.
ARMA Model (Subbarao, 1986)		X		Autoregressive Moving Average model.
ARMA Model (Reddy, 1989)		X		Multiple-input autoregressive moving average model.
BEVA, PSTAR (Subbarao, 1986)	X	X	X	Combination of ARMA and Fourier series, includes loads in time domain.
Modal analysis (Bacot et al., 1984)	X	X	X	Bldg. described by diagonalized differential equation using nodes.
Differential equation (Rabl, 1988)		X		Analytical linear differential equation.
Computer simulation (DOE-2, BLAST)	X		X	Hourly simulation programs with system models.
Computer emulation (HVACSIM+, TRNSYS)	X		X	Sub-hourly simulation programs.
Artificial neural networks (Kreider and Wang, 1991; Kreider, 1992; Kreider and Haberl, 1994)		X	X	Connectionist models.

A.3 Decision support for selection of methodology. [Kreider et al. 2010]

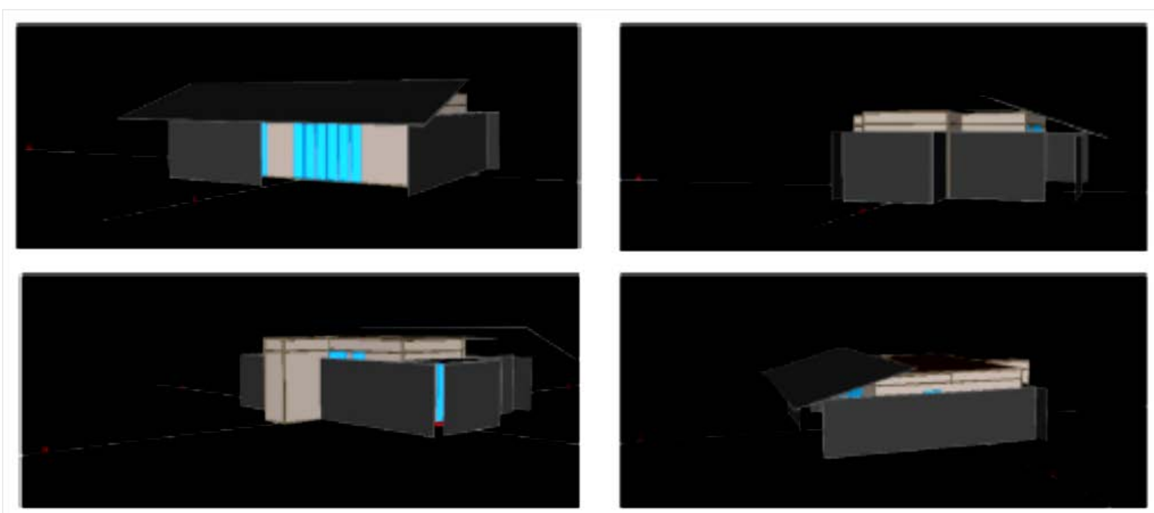
Method	Usage[a]	Difficulty	Time[b] Scale	Calc. Time	Variables[c]	Accuracy
Simple linear regression	ES	Simple	D,M	Very Fast	T	Low
Multiple linear regression	D,ES	Moderate	D,M	Fast	T,H,S,W,t	Medium
ASHRAE bin method and inverse bin method	ES	Moderate	H	Fast	T	Medium
Change point models.	D,ES	Moderate	H,D,M	Fast	T	Medium
ASHRAE TC 4.7 modified bin method	ES,DE	Moderate	H	Medium	T,S,tm	Medium
Thermal network	D,ES,C	Complex	S,H	Fast	T,S,tm	High
Fourier Series Analysis	D,ES,C	Complex	S,H	Medium	T,H,S,W,t,tm	High
ARMA Model	D,ES,C	Complex	S,H	Medium	T,H,S,W,t,tm	High
Modal analysis	D,ES,C	Complex	S,H	Medium	T,H,S,W,t,tm	High
Differential equation	D,ES,C	Very Complex	S,H	Fast	T,H,S,W,t,tm	High
Computer Simulation (Component-based)	D,ES,C, DE	Very Complex	S,H	Slow	T,H,S,W,t,tm	Medium
Computer simulation (Fixed schematic)	D,ES,DE	Very Complex	H	Slow	T,H,S,W,t,tm	Medium
Computer emulation	D,C	Very Complex	S,H	Very Slow	T,H,S,W,t,tm	High
Artificial Neural Networks	D,ES,C	Complex	S,H	Fast	T,H,S,W,t,tm	High

[a] Usage shown includes diagnostics (D), energy savings calculations (ES), design (DE), and control (C).
[b] Time scales shown are hourly (H), daily (D), monthly (M), and subhourly (S).
[c] Variables include temperature (T), humidity (H), solar (S), wind (W), time (t), thermal mass (tm).

A.4 SHADE - eQUEST - Simulation model

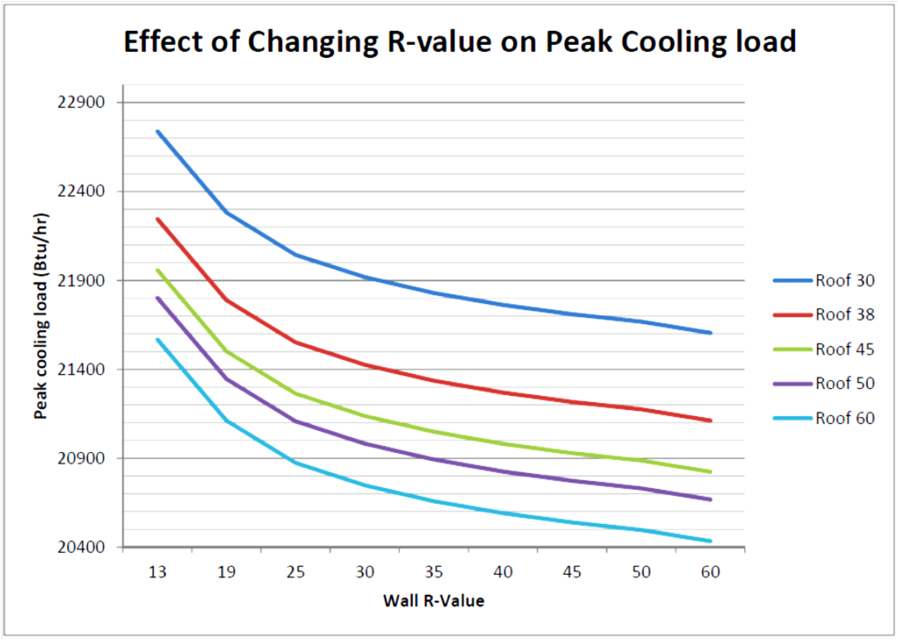
As an exercise in forward modeling mentioned briefly in section 3.2 following are examples of simulations for the SHADE house that informed the design process for the insulation, for the PV System.

The eQUEST model revealed the largest contributor to the solar heat gain in the SHADE home is the Bi-Fold Door on the south facing wall at the patio. The second largest contributor to the solar heat gain is the roof. The model and the graph below highlight the expected cooling loads based on the thickness of insulation used and a spreadsheet based evaluation using the Cooling Load Temperature Difference CLTD + Cooling load Factor CLF method. This was a short hand non dynamic calculation method not accounting for the transient effect of the thermal mass of the building.



ZONE 1	Net area (ft^2)	GLF (h ft^2)	U- value (Btu ft^2 F)	CLTD (F)	Cooling load (Btu/h)
N wall	81.67		0.025	23	46.96025
W wall	78.33		0.025	33	64.62225
S wall	85.83		0.025	26	55.7895
Bathroom partition	0		0.066666667	19	0
Roof	177.843		0.02	56	199.18416
W window	26	50	0.51		1300
N window	29.28	50	0.45	23	1464
Infiltration	1778.43				470.809702
Floor	177.843		0.02	19	67.58034
					`

[Study part of ATE - 556 - Group - Apoorva, Rahul]



SHADE - Example of the Combined Heat Transfer Calculation for the Building Envelope [ASHRAE template for CLTD - Kreider CD ATE - 582]

Roof		Component	thickness (")	Thickness (ft)	Conductivity (Btu/h-ft-°F)	Density (lb/ft3)	Spec. Heat (Btu/lb-°F)	R-Value (h-ft2-°F/Btu)
	Roof Type 1 - p1 With Joists							
		Air Film Outside Resistance						0.07000
		Spray Soy Foam (R=7.2 (7/in))	1.00000	0.08333				7.00000
		Radiant Barrier	* not necessary in conductive Heat Transfer					
		Rigid Insulation (R=6 (5.5/in))	**6.00000**	**0.50000**				**33.00000**
		3/4 " sheathing Plywood	0.50000	0.04167	0.80000			0.05208
		Joists 9"	0.05400	0.00450	26.20000			0.00017
		PCM Q23 M51	* accounted for in zone heating/ cooling					
		Durarock Board	0.50000	0.04167	0.78740			0.05292
		Cementetious Plaster	0.25000	0.02083	0.21000			0.09921
		Indoor Air Film						0.68000
						Total R-roof p1		40.95438
					Percent of the 1 x 1 ft roof Area			0.33000
	Roof Type 2 - p2 Without Joists							
		Air Film Outside Resistance						0.07000
		Spray Soy Foam (R=7.2 (7/in))						7.00000
		Radiant Barrier	* not necessary in conductive Heat Transfer					
		Rigid Insulation (R=6 (5.5))	**6.00000**	**0.50000**				**33.00000**
		3/4 " sheathing Plywood	0.50000	0.04167	0.80000			0.05208
		Spray Soy Foam (R=7.2 (7))	8.00000	0.66667				56.00000
		PCM Q23 M51	* accounted for in zone heating/ cooling					
		Durarock Board	0.50000	0.04167	0.78740			0.05292
		Cementetious Plaster	0.25000	0.02083	0.21000			0.09921
		Indoor Air Film						0.68000
						Total R-roof p1		96.95421
					Percent of the 1 x 1 ft roof Area			0.66000
				Total R VALUE of Roof (0.33 p1 + 0.66 p2)				67.27174
				Effective UA Roof (Excludes PCM)				**0.01487**

A.5 SHADE - Energy Consumption based on appliance energy use [NREL] [Study part of ATE/SOS - 598]

APPLIANCE	Rating (Watts) - Pickup	NUMBER OF TIMES SWITCHED ON	TOTAL HOURS COMPETITION FOR (9 DAYS) IRVNE	Annual Hourly Use PHOENIX D Avg.	Annual Hourly Use PHOENIX ANN	TOTAL ENERGY COMPETITION ONLY (9 DAYS) IRVNE	Annual Energy Use (KWH) PHOENIX
HVAC							
RENEWAIRE ERV U- EV 90	45	44	44	3.5	1278.375	1983.96	14.38
MAGNA 32-100 F N, EcoCirc Pump (TSU)	85	72				12.24	
MAGNA 32-100 F N, EcoCirc Pump (BEKA)	85	36				6.12	
HEAT PUMP/ CHILLER (COMPRESSOR)	3000	42	21	4	1461	21252	1095.75
CONTROLLER - HP/ COMP	10	420				8.4	
MODULATING VALVES (TRI)	10	432				8.64	
MODULATING VALVE 2	10	864				17.28	
TRANE FAN COIL FC MODEL P	2500	44	22	4	1461	5720	913.12
CONTROLLER - ZONE VALVES (FLOW RATE)	0.5	440				0.44	
CONTROLLER - DAMPER - HYBRID RECOVERY	0.5	440				0.44	
CONTROLLER - DAMPER - VENTILATION RECOVERY	0.5	440				0.44	
CONTROLLER/ LOGGER	0.5	440				0.44	
DOMESTIC WATER / HOT WATER/ FIRE							
FROM QUAIL PLUMBING -	750	65	4			1811.785714	
ATI 66 HP WATER HEATER	5500	8	3	1.1	401.775	8338	441.95
GREY WATER REMOVAL PUMP							
PUMP - not counted towards Energy Analysis out of Competition	750	18	0.45	NA	NA		
HOME APPLIANCES							
ZBD1870NSS: GE Monogram 18" Dishwasher	550	12	10	0.571	208.55775	5513.2	28.67
PS905SPSS: GE Profile 30" Slide-in Electric Range	11600* (800)	12	16	1.5	547.875	12819.2	438.3
Bake / Broil	3600* (350)	2	2	0.28	102.27	7214.4	35.79
PFCs1RKZSS: GE Profile Energy Star 20.9 cuffs. French-door Bottom-Freezer Refrigerator	1800	3	192	24	8766	20790	1577.88
GFWH1200DWW: GE Energy Star 36 DOE cuff. capacity Front-load Washer	2400	9	7.2	0.28	102.27	17323.2	245.44
GFDN120EDWW: GE 7.0 cuff. capacity Electric Dryer	5600	9	7.2	0.42	153.405	18020.8	214.76
Insignia™ - 39" Class (38-1/2" Diag.) - LED - 1080p - 60Hz - HDTV	75	17	34	3.5	1278.375	2552.55	19.175
Samsung 7 series NP770Z7E-S01UB	60	17	34	5	1826.25	2042.04	109.57
Bose L1 Compact Speakers	900	3	6	1.5	547.875	5405.4	493.08
1Projector	1000	1	2.5	0.16	58.44	2502	58.44

LIGHTING							
Tech lighting pod - (6 nose)	6	10	180	3	1095.75	1080.12	6.57
Tech Lighting Piper - (2 nose)	6	10	60	6	2191.5	360.12	13.14
Cooper Lighting LC32 LED - (6 nos)	14	10	180	4.5	1643.625	2520.28	23.01
Cooper Lighting 493 Solute - (3 nos)	6	10	108	1	365.25	648.12	2.19
Cooper Lighting Halo LED Module - (3 nos)	20	10	90	2	730.5	1800.4	14.61
Ikea HAGGAS - (1 nos)	3	10	36	0.2	73.05	108.06	0.21
Progress Lighting Cylinder (3 nos)	14	10	90	3	1095.75	1260.28	15.34
Hafele Loox LED 2013 (2 nos)	25	10	60	2	730.5	1500.5	18.26
Hafele LED 2002 (5 nos)	1.5	10	180	1	365.25	270.03	0.54
Driver Loox LED Driver (3 nos)	30	10	108	3	1095.75	3240.6	32.87
FX Luminare LE (7 Nos)	2	10	252	0.65	237.4125	504.04	0.474
FX Luminare LE (14 Nos)	2	10	420	0.9	328.725	840.04	0.657
Luxor Transformer (1 Nos)	150	10	36	0.9	328.725	5403	49.308
CONTROLS & MISC LV	10					Add 1.5 %	
TEKMAR - CONTROLS FOR BEKA							
LUTRON CONTROLS radio ra 2 repeater							
NEXIA CONTROLS							
FAN COIL CONTROLS							
PHANTOM CIRCUIT LOSES	35			18	365.25		12.78
CIRCUITS/ RELAYS AND BREAKERS - HVAC							
CIRCUITS/ RELAYS AND BREAKERS – CARPORT							
CIRCUITS FOR APPLIANCES							
CIRCUITS/ PUMPS							
CIRCUIT/ INVERTERS							
TOTAL KWH						153	5864

A.6 SHADE - Forward models for PV sizing [NREL - derate factoring]

PV Sizing			**Formula**	**Phoenix** **(Grid Tied) - net metering**		**IRVINE** **Competition - 9 Days** **Grid Tied**	
Determine power consumption demands							
Watt hrs Per-Day (Appliance demand)				16053.59	Watt-h per day	16986.51	Watt -h per day
Circuit Losses and Safety factor - 30 %			**[eq. 1.1] * 1.3**	**20869.66**	Watt-h per day	**22082.46**	Watt - h per day
Watt hrs based on MAX Demand. + Battery charge - (FOR STAND ALONE ONLY)							
Total Watt Per Hrs Needed to be Produced by PV during that day.							
Determine Peak Watts needed from PV with the available Sun Hours (PSH)	**WINTER**	**AVG**					
Average Annual PSH (Phoenix)	5	5.5		**5.5**	AVG - PSH		
Total Watt-peak rating needed for the PV panels needed to operate the appliances			**[eq. 1.3] * 1 / [eq. 2.1]**	**3794.48**	Watts -peak		
Total Watt - peak rating for WINTER - WORST CASE SCENARIO			**[eq. 1.3] * 1 / [eq. 2.1 winter]**	**4173.93**	Watts -peak	4	PSH
Total Watt - peak rating for Max Coincidental demand by Appliances * for Stand Alone in Winter	(Refrigerator + Airconditioner + 50% Lighting + 50 %Appliances)					5520.61	Watts Peak
Effective total Watt-peak rating for PV modules - DEDUCTIONS - Derate Factor							
(Using Solar World -250 Watts - Panel Specs attached.							
At 1 SUN - 250 Watts at **0.80 SUN - performs at 180.8 Watts.)**				250	Watts	250	Watts
Considering 0.95 Sun Rating.				237.5	Watts	237.5	Watts
Temperature reduction factor recommended by the **CEC for Phoenix** is 0.89.			**[eq. 3.1] * 0.89**	211.38	Watts	211.38	Watts
Soiling : Dust reduction factor to use is 0.93.			**[eq. 3.2] * 0.93**	196.58	Watts	196.58	Watts
Mismatch and Wiring losses - 0.98			**[eq. 3.3] * 0.98**	192.65	Watts	192.65	Watts
Diodes and Connections - 0.99			**[eq. 3.4] * 0.99**	190.72	Watts	190.72	Watts
DC to AC Conversion Losses - 0.97			**[eq. 3.5] * 0.97**	185.00	Watts	185.00	Watts
System Down Time/ Maintenance - 0.98			**[eq. 3.6] * 0.98**	181.30	Watts	181.30	Watts
Solar Orientation for fixed							
Deviation from True South Orientation - due to magnetic/ true south variation	10 deg	West of south					
19 deg 33-19=14 (14 % reduction due to incorrect tilt)	19 deg	0.85	**[eq. 3.8] * 0.85**	**154.10**	Watts	**154.10**	Watts
Size of the Array - Number of PV Panels Needed							
Number of Panels needed for Total Watt-Peak Rating			**[eq. 2.2] * 1 / [eq. 3.5]**	24.62	Panels	35.82	Panels
Rounded Off to 32 panels to cover **100 % Annual Energy Consumption** of the House.	(Potentially Stand Alone)			**28**	**Panels**	**36**	Panels
Worst case Instantaneous Peak Demand (refrigerator + dryer + AC + Cooking + Appliances)	6918	Watts	**Winter**				
Voltage at Maximum Power point **(Name Plate)**	31.1	Volts					
Typical Voltage of House System	230-240	Volts		(7 modules in series) x 4 Strings		6 Series x 6 parrallel Strings	
Voltage for combined PV configuration **8 in Series (Additive)**			7 x 31.1 Volts	**217.7**	Volts	**186.6**	Volts
Amperage for the panel **(Name Plate)**	8.05	Amps					
Amperage for **4 Parallel Strings** for (7 Series Solar modules)			4 x String	**32.2**	Amps	**48.3**	Amps
Effective Watt form the Array at 1 Sun			**[eq. 5.5]**	**7009.94**	Watts	**9012.78**	Watts

A.7 Details of the instrumenttion

Appendix C Measured Subcontest Guidelines

C-1. Monitored Performance Subcontests

Table 5 lists sensors used[13] in the "monitored performance" subcontests for which points are automatically awarded based on measurements made by each home's datalogger. Purchasing information is provided for teams intending to practice the contests before the competition using the same equipment that will be used by the organizers.

Table 5: Sensors used in "measured performance" subcontests

Subcontest(s)	Sensor Type	Vendor	Model Number	Approx. Price
6-1. Temperature 6-2. Humidity	Temperature/humidity probe	Campbell Scientific (probe)	HMP50 probe	$425
8-1. Refrigerator	Thermocouple wire	Omega Engineering	TT-T-24S-TWSH-SLE-100	$141
8-2. Freezer	Thermocouple wire	Omega Engineering	TT-T-24S-TWSH-SLE-100	$141
Contest 10. Energy Balance	Utility revenue-grade meter	GE	kV2c Encompass electronic meter family with KYZ output	$150

Table 6 lists the central data acquisition equipment and associated accessories that collect sensor readings and transmit the data to the scoring server. Please refer to the documents[14] in the "/Files/Rules/Rules Reference Documents" folder on the Yahoo Group for detailed policies and procedures for accommodating competition instruments.

Table 6: Central data acquisition equipment

Equipment Description	Vendor	Model Number	Approx. Price
Datalogger enclosure	Hubbell-Wiegmann	ENC12/14-DC-NM	$235
Datalogger	Campbell Scientific	CR1000	$1,400
Power supply	Campbell Scientific	PS100	$225
Transformer	Campbell Scientific	9591	$50
Ethernet interface	Campbell Scientific	NL120	$220
Sensor wire and miscellaneous parts	Various	Various	$125

The "task completion" subcontests listed in Table 7 are classified as such because teams earn points by successfully completing a task that is observed by, and the results of which are recorded by, an observer in the "observer logs":

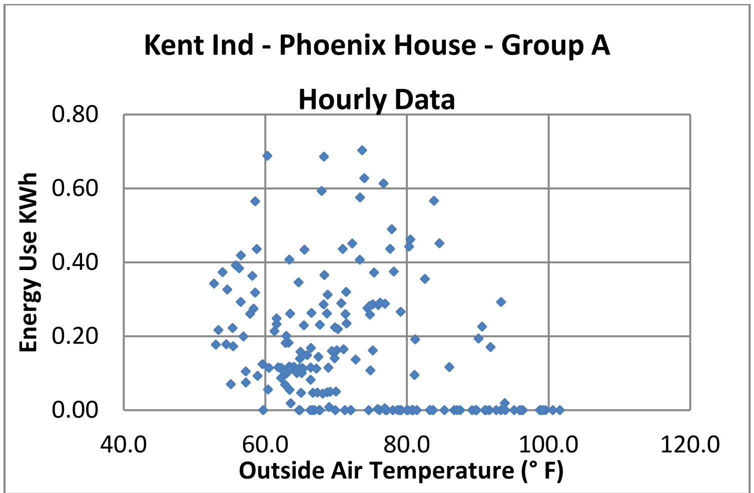
Table 7: Instruments and sensors used in "task completion" subcontests

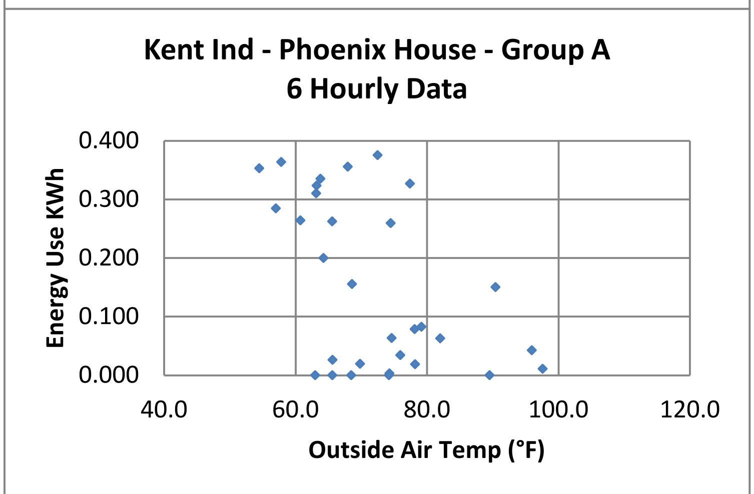
Subcontest(s)	Instrument or Sensor Type	Vendor	Model Number	Approx. Price
Contest 7. Hot Water	Multiple Components[15]	Constructed	None	$600
8-3. Clothes Washer	Visual/audible inspection	n/a	n/a	n/a
8-4. Clothes Dryer	Scale	Acculab	SVI-50C	$350
8-5. Dishwasher	Nonreversible temperature label	Omega	TL-5-105-10	$10 (pkg of 10)
9-1. Lighting	Visual inspection	n/a	n/a	n/a
9-2. Cooking	Kitchen scale	Salton	1008	$50
9-4. Home Electronics	Visual inspection	n/a	n/a	n/a

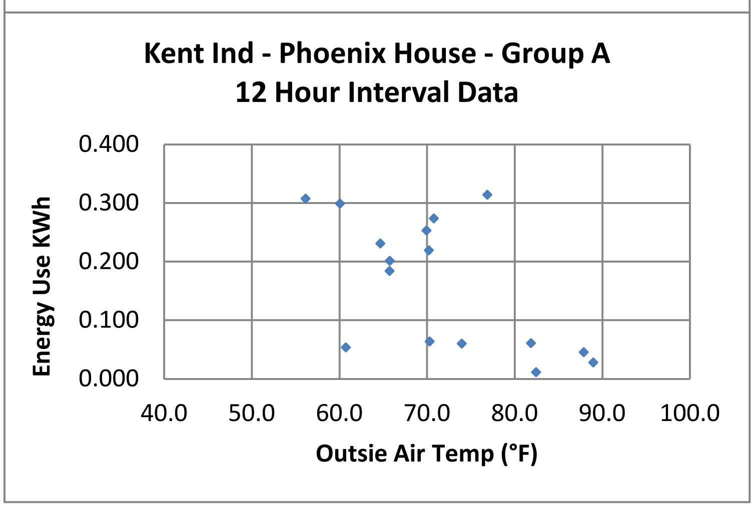
A.8 Details of end use appliance data. (Blanks are missing data)

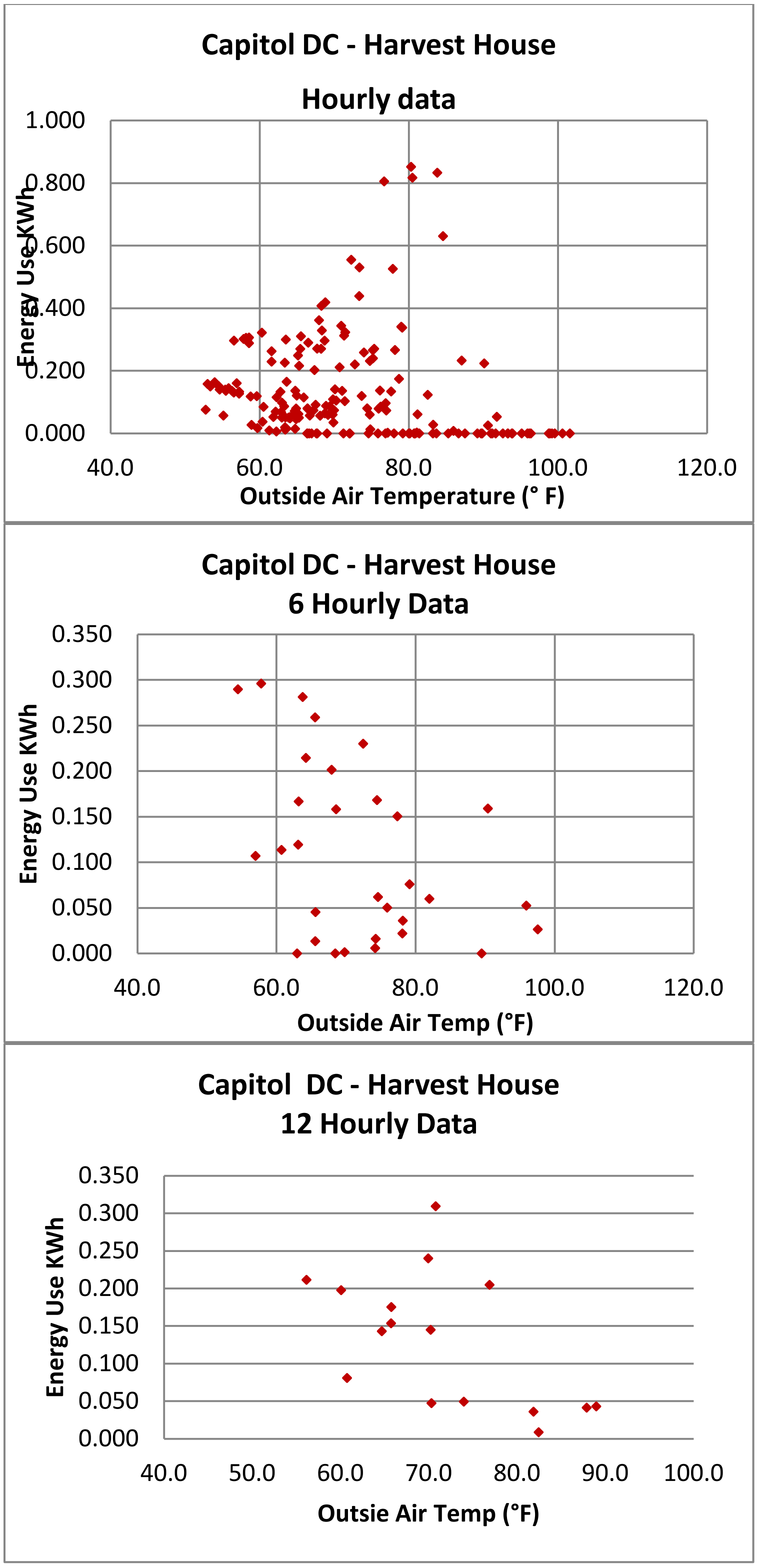
House	INSULATION	A/C	DHW	Refrigerator	Lighting	Range/ Oven	Music/ Applia	mestic Water Pu	Washer/ Dryer	Dishwasher
BOREALIS	ROOF - 38 WALLS - 39.5 FLOOR -28 GLAZ > 35%	AIR-BASED HIGH VELOCITY AIR HANDLER	SOLAR THERMAL + ELECTRIC COIL	BLOMBERG BRF81450	LED LIGHTING	MAYTAG UXT5230AYS		RED LION RJ8-50E	BLOMBERG WM7710 BLOMBERG DV7542	BOSCH SPXE855UC
SHADE	ROOF - 55 WALLS - 40 FLOOR - 30 GLAZ > 35%	HYBRID WATER BASED SCROLL WATER CHILLER + RADIANT DISTRIBUTION	HYBRID HEAT PUMP + ELECTRIC COIL		LED LIGHTING			GOULDS TECH J 115		
HARVEST	ROOF - 38 WALLS - 20 FLOOR - 19 GLAZ	AIR-BASED HEAT PUMP CENTRAL AIR-HANDLER WITH DUCTED	HYBRID - FLAT PLATE SOLAR THERMAL + AUXILLARY ELECTRIC COIL	440 KWh Annual	LED + FLOUROSCENT	2.kw @ 240 V OVEN	2 SCREENS	100 W @ 120 v	96 KWh Annual (8 lds/week) 5.4 KW- 240 V	267 KWh Annual (4 lds/week)
PHOENIX HOUSE	ROOF - 60 WALLS - 33 FLOOR - 20	AIR BASED WTH ECONOMIZER	ELECTRIC COIL WATER HEATER		LED + FLOUROSCENT			DAYTON 1D876		
DESERTSOL	ROOF 55 WALL 30 FLOOR 45	AIR BASED SPLIT SYSTEM + ERV	SOLAR THERMAL + ELECTRIC COIL INSTANT		LED + FLOUROSCENT					
INSITE		AIR BASED SPLIT SYSTEM + ERV	ELECTRIC COIL WATER HEATER		LED + FLOUROSCENT			GRUNFOS PRESSURE PUMP		
CHAMELEON		AIR BASED SPLIT SYSTEM + ERV	ELECTRIC COIL WATER HEATER		LED + FLOUROSCENT			FloJEt 3500		
URBAN EDEN	ROOF 55 WALL 30 FLOOR 30	AIR BASED SPLIT SYSTEM AIR/ AIR + SOLAR THERMAL - RADIANT HEATING IN WALLS	HEAT PUMP HOT WATER + SOLAR WATER		LED + FLOUROSCENT					
ECHO		AIR BASED SOLAR ASSISTED HEAT PUMP + ERV	SOLAR THERMAL + AUXILLARY ELECTRIC COIL INSTANT		LED			0.5 HP SUPPLY PUMP + SUBMERSIBLE PUMP		
RADIANT HOUSE		HYBRID WATER BASED MODULAR CHILLED CEILING + MINI SPLIT	HEAT PUMP WATER HEATER WITH AUXILLARY ELECTRIC COIL		LED			0.9 KW/H PRESSURE PUMP		
DALE	ROOF 30 WALLS 23 FLOOR 24	AIR BASED HEAT PUMP WITH 2 INDOOR TERMINALS	SOLAR THERMAL EVACUATED TUBES		LED + FLOUROSCENT					
START.HOME		AIR BASED TRI ZONE MINI SPLIT + ERV	ELECTRIC COIL + HEAT PUMP		LED + FLOUROSCENT					
ECOHABIT	ROOF 46 WALLS 34 FLOOR 34	AIR BASED SPLIT SYSTEM	HYBRID HEAT PUMP+ ELECTRIC COIL		LED			FLOJET PUMP		
FLUXHOME		AIR BASED HEAT PUMP + INDOOR TERMINAL	SOLAR THERMAL + HEAT PUMP + ELECTRIC COIL		LED			GRUNDFOS MQ3-45		

A.9 Example graphs for Energy Signature Scatterplot - Whole building energy use hourly, 6 hourly and 12 hourly interval vs Temperature (Hammarsten model, 1987)









Three graphs shows comparison of Energy use with OA temperature from a randomly selected house from Group A and Group B.

APPENDIX B

DATA FROM EXTERNAL SOURCES

Million Housing Units, Final						
		Housing Unit Type				
		Single-Family Units		Apartments in Buildings With		
Fuels Used and End Uses	Total U.S.[1] (millions)	Detached	Attached	2 to 4 Units	5 or More Units	Mobile Homes
Total Homes	113.6	71.8	6.7	9.0	19.1	6.9
Fuels Used for Any Use						
Electricity	113.6	71.8	6.7	9.0	19.1	6.9
Natural Gas	69.2	45.6	4.7	6.1	11.0	1.8
Propane/LPG	48.9	39.6	2.4	1.7	2.0	3.2
Wood	13.1	11.4	0.3	0.2	0.5	0.7
Fuel Oil	7.7	5.1	0.4	0.7	1.3	0.1
Kerosene	1.7	1.1	Q	Q	Q	0.5
Solar	1.2	1.1	Q	Q	Q	Q
Electricity End Uses[2] (more than one may apply)						
Space Heating	58.0	35.2	3.3	4.3	10.1	5.0
Main	38.1	20.0	2.1	3.3	8.9	3.9
Secondary	26.8	19.7	1.7	1.7	2.1	1.8
Air Conditioning	94.0	61.1	5.6	6.3	15.2	5.8
Water Heating	47.1	27.5	2.3	3.3	8.7	5.2
Cooking	71.2	46.0	4.0	4.8	12.3	4.1
Other	113.6	71.8	6.7	9.0	19.1	6.9
Natural Gas End Uses[2,3] (more than one may apply)						
Space Heating	57.2	39.7	3.9	4.7	7.5	1.4
Main	55.6	38.5	3.9	4.6	7.2	1.4
Secondary	7.2	6.2	0.4	0.1	0.4	Q
Water Heating	58.4	38.8	4.1	5.2	9.2	1.1
Cooking	39.2	25.0	2.7	3.9	6.3	1.3
Other	21.5	18.2	1.2	1.0	0.8	0.4
Propane/LPG End Uses[2,3] (more than one may apply)						
Space Heating	8.0	6.5	0.2	0.1	0.1	1.1
Main	5.6	4.4	0.1	0.1	Q	0.8
Secondary	2.8	2.5	Q	N	Q	0.2
Water Heating	4.2	3.2	Q	0.2	0.3	0.5
Cooking	5.7	4.1	Q	0.1	Q	1.4
Other	43.9	36.3	2.3	1.6	1.6	2.1
Wood End Uses[2] (more than one may apply)						
Space Heating	11.5	10.1	0.3	0.1	0.5	0.6
Main	2.8	2.5	Q	N	Q	0.3
Secondary	8.8	7.7	0.2	0.1	0.5	0.3
Other	1.7	1.5	Q	Q	Q	0.1
Fuel Oil End Uses[2] (more than one may apply)						

Space Heating	7.3	5.0	0.4	0.6	1.2	0.1
Main	6.9	4.7	0.4	0.6	1.2	Q
Secondary	0.4	0.3	Q	Q	Q	Q
Water Heating	3.6	2.5	0.2	0.3	0.6	Q
Other	0.2	0.1	Q	N	Q	Q
Kerosene End Uses[2] **(more than one may apply)**						
Space Heating	1.4	0.8	Q	Q	Q	0.4
Main	0.5	0.2	Q	N	Q	0.2
Secondary	0.9	0.6	Q	Q	Q	0.2
Other	0.3	0.3	Q	N	N	Q

[1]Total U.S. includes all primary occupied housing units in the 50 States and the District of Columbia. Vacant housing units, seasonal units, second homes, military housing, and group quarters are excluded.

[2]Cooking includes fuels used by the major cooking equipment (ovens, cooktops, and stoves). Other includes all end uses not specificially listed.

[3]For natural gas and propane/LPG, Other includes housing units with outdoor grills that use these fuels. However, Consumption and Expenditures estimates only include natural gas outdoor grills, not those using propane/LPG.

Q = Data withheld either because the Relative Standard Error (RSE) was greater than 50 percent or fewer than 10 households were sampled.

N = No cases in reporting sample.

Notes: ● Because of rounding, data may not sum to totals. ● See Glossary for definition of terms used in these tables.

Source: U.S. Energy Information Administration, Office of Energy Consumption and Efficiency Statistics, Forms EIA-457 A and C of the 2009 Residential Energy Consumption Survey.