EVALUATION OF IN-SITU COOLING PERFORMANCE AT RENOVATION2050:

COMPARING ZONE VS. CENTRAL BASED COOLING SYSTEMS FOR SINGLE FAMILY DWELLINGS

By

Anthony Guadagnoli, B.Eng., Ryerson University

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ABSTRACT

The objective of this Major Research Project has been to compare the benefits of cooling performance of zoned and central air conditioning systems using summer 2013 as an evaluation period. Three adjacent houses in Toronto have been studied as part of the Renovation2050 research program. Total cooling energy usage was measured directly from all cooling equipment, along with temperature and relative humidity readings via remote sensors. The goal of this 1-year study was to compare the cooling energy performance of each house, temperature, and relative humidity. The study has used energy simulation, to compare zoned and central systems while accounting for weather, human occupancy, and construction types. Results have shown that there is potential for energy benefits on a zoned system compared to a central system by approximately 95% in total cooling energy use for the study period, and these results are dependent on the building envelope and user types.

Acknowledgements

The author would like to thank Dr. Russell Richman for his support during this Major Research Project. Dr. Richman has provided valuable input and guidance to the approach and design of this research project, his time and effort are greatly appreciated on this project and towards the completion of his Master degree.

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1.0 INTRODUCTION

Renovation2050 has been an initiative towards sustainable renovation for existing residential dwellings within downtown neighbourhoods. The first research house (Reno2050) under this initiative was completed in 2010[1], and has undergone a deep energy retrofit. It involves the study and application of building science theory, whereby the design, construction and performance of this dwelling has been used to complete several research initiatives. This Major Research Project (MRP) focuses on cooling energy performance over summer 2013 where mechanical systems (air conditioners) have been compared across three neighbouring houses, and the benefits of zone cooling vs. central cooling have been evaluated.

The Canadian housing stock constitutes over 17% of Canadian end-use energy consumption [2] and 1% of this is related to space cooling [3]. The percentage of occupied floor space cooled rose from 23 percent in 1990 to 44 percent in 2009 [4]. With the current building stock aging, there is potential for energy savings through building envelope energy retrofits and improvements. In 2006, 60% of Canada's building stock was 30 years old or greater [5]. In Canada's cold climate, much focus has been on the energy savings over the heating season[6]; however the effects on the cooling season from these retrofits has not been fully understood and at times appears to be have overlooked within other literature. The first air conditioner was installed on the New York Stock Exchange in 1902 [7]; today air conditioning is now common in all buildings. Over the last several decades, consumer demand for air conditioning has increased rapidly. In 1960's approximately 12% of houses in the United States had air conditioning; in 2005 there were approximately 82% of houses with it [8]. The Ontario Building code does not specifically require air conditioning for a house, but approximately 53% of Ontarians have air conditioning systems [9].

The principle purpose of an Air Conditioning (AC) system is to provide cooling for its occupants. While conventional AC systems can provide this, these systems are often oversized; designed to extreme climate conditions and often operate on partial loads thus consuming more energy [10]. This research measured and compared the energy usage of three houses with different cooling systems and different building envelopes over summer 2013. The purpose of the comparison was to map the cooling performance of Reno2050, a zone-cooled house, against adjacent houses of similar vintage, size and occupants, utilizing central air-conditioning systems. In order to normalize the field results, energy simulation was conducted. Alongside energy use, the study has also measured and compared temperature and relative humidity throughout the houses via a network of remote sensors in order to validate the comfort ‘success’ associated with the cooling equipment.

1.1 OBJECTIVE AND RESEARCH QUESTIONS

The objective of this study was to evaluate the performance of Reno2050’s zone cooling approach and compare it to adjacent centrally cooled houses. The research questions that arise from this study are as follows:

1. What are the energy benefits of zone cooling compared to central air cooling systems?
2. What are the comfort benefits (i.e. temperature and relative humidity) across houses with zone cooling and central air cooling systems?

1.2 REPORT ORGANIZATION

This organization of this MRP will first present a summary of literature reviewed related to the topic of zone and central cooling systems. A methodology section will follow presenting the method for which this study was carried out. A field study preparation section with relevant background information on the test houses followed by results and discussion sections will also be presented.

2.0 LITERATURE REVIEW

The literature review focused on research articles, reports and field studies researching energy benefits of zone cooling systems and conventional forced air cooling systems. The selected literature covered other similar field-testing programs and relevant articles on residential cooling energy performance, building envelope and interior temperature and relative humidity studies. The literature review was not exhaustive in nature; however there was generally a lack of literature pertaining to this specific topic as well limited field studies with validation measurements.

Cooling Systems

ASHRAE HVAC fundamentals states that the three main types of residential mechanical systems are the central forced air system, central hydronic and zone systems [10]. System selection and design is based on many factors including energy source, means of distribution, delivery and terminal devices. Figure 1 shows a conventional central forced air system: when cooling is required, heat and moisture are removed from the circulating air that passes across the evaporator coil. Refrigerant lines connect the evaporator coil to a condensing unit located outdoors. Figure 2 shows a typical mini-split system for a two-zone ductless system. In this example, the mini-split system consists mainly of two parts: an outdoor condensing unit and two indoor air-handling units, installed on perimeter walls of the house. Each air handler can serve one zone controlled independently from the other units.

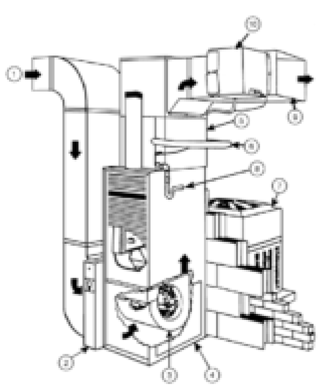


Figure 1: Typical residential heating, cooling, humidifying and air filtering system [10].

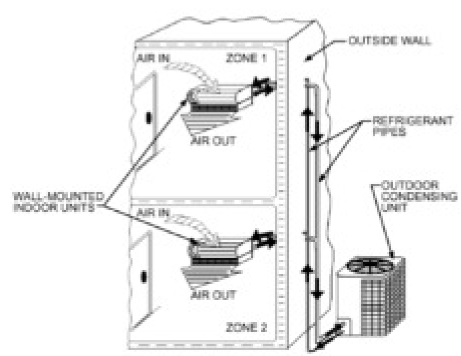


Figure 2: Example of two-zone, ductless mini-split system in typical residential installation [10].

Air conditioning (AC) technology varies between the two systems, but both make use of a compressor which is the heart of any AC. Ductless min-split systems employ an inverter compressor, the more common central AC systems use rotary or scroll compressors [11]. Rotary or scroll compressors typically operate in a constant on-to-off setting, and lacks the ability to vary its cooling output capacity, thus it has the tendency to switch on and off dozens of times within a day. Alternatively, inverter compressors operate with variable speeds, thus operating at higher outputs than a standard compressor. Research indicates that an inverter compressor operates with 50% less energy required than a rotary compressor [11]. The lifespan of the inverter compressor also increases dramatically, since it has less cycling than a rotary compressor. Inverter compressors appear to have superior performance; however, an accurate comparison of the two systems in a complete house setting with representative operating conditions is required to compare the systems. The subject MRP studied the above technology within zoned and central cooled systems; the setup consisted of occupied houses where actual energy use was recorded over an entire summer in 2013.

The performance assessment of a variable capacity air source heat pump (ASHP) and a horizontal loop ground source heat pump (GSHP) was conducted at the “Archetype Test houses” site located in Vaughan, Ontario [12]. The study evaluated the energy consumption over the heating and cooling seasons for the houses. The two houses have similar construction and size, and infiltration air leakage rates of 1.2 ACH and 1.1 ACH at 50Pa. House A (with ASHP) had a 10.3 kW high efficiency variable capacity air-to-air source heat pump with a direct expansion coil air handling unit (AHU). House B (with GSHP) consisted of a 13.3 kW high efficiency ground source heat pump connected to two 150m horizontal loops in the yard. For the summer season, data was recorded between August to September 2010 through a series of sensors setup throughout the houses. The ASHP outperformed the GSHP during the cooling season by approximately 29% for energy consumption. The ASHP had variable capacity leading to lower cycling of the compressor, and has showed better performance for the zoned system (ASHP) compared to the GHSP, however the field study was conducted in unoccupied homes and was limited to a 1-month study period. This MRP studies three houses for an entire summer period in 2013. The houses were fully occupied during this period. The results from the “Archetype Test house” have been in favor of a zoned system for energy performance; however, a more controlled setup to measure the differences between zone and central cooling systems has been carried out in this MRP.

A study on cooling energy performance for three side by side homes in South Texas was conducted over two years in 2009 to 2010 [13]. All of the homes had identical floor plans and orientation, single storey and timber framed and less than 2,000 ft^2 in size. One home was constructed to builder's standards (least performance) and the other two built to high performance standards. Energy savings ranged between 55% to 77% for cooling use and 28% to 68% for peak AC load reduction. Overall the high performance homes had the most energy savings due to improvements with building envelope, air leakage rates and high efficiency AC equipment. This study has validated significant energy savings for high performance houses with high efficient central cooling systems, however further study is still needed in this area. The study only addresses single storey homes with timber frame structures and of new construction vintage, the subject MRP has existing houses with solid masonry construction built 3 storeys high, located within Canada's climate. Furthermore, it does not address the in-situ cooling performance between different types of cooling systems (zoned and central); this MRP will attempt draw a comparison on these systems.

ASHRAE published an article "Field Observations of Room to Room Air Distribution Performance in Two Rooms of a Cold Climate House" [14]. The purpose of this study was to compare room air distribution of two similar rooms with different register locations (high wall and floor mounted register) on a conventional forced air system. The impact of normal equipment cycling has also been investigated. The study was compared to the ASHRAE 55 Thermal Comfort Standard: "When temperature fluctuations are involved, the rate of temperature change should not exceed (2.2°C/h) when the temperature variation exceeds 1.1°C in a 15-minute period."[15] The study concludes that both high wall and floor mounted register locations do not experience short-circuiting of the systems and they both satisfy the ASHRAE thermal comfort standard. Refer to Figure 3 for operative range guidelines set out by ASHRAE. The floor mounted register location is common in a central AC system, where high wall supply location would be provided in a zoned AC system. The study shows that air distribution is generally not effected for a single room with low or high wall supply locations, however a discussion on the impacts of register locations within a multi-storey house application has not been presented. Furthermore, energy use was not mentioned in this article. In order to compare zoned and central cooling systems this MRP will study both energy use and the indoor climate conditions.

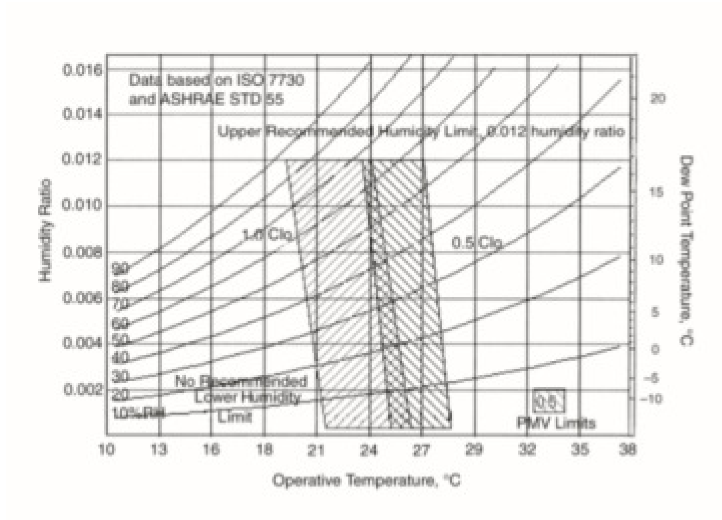


Figure 3: Acceptable range of operative temperature and relative humidity for spaces that meet ASHRAE 55.[14]

Ductless Mini-Split Systems

A common zoned system for a residential application is a ductless mini-split air conditioner [16]. Like central systems, mini-splits have two components: an outdoor condenser and an indoor air handling unit, between these units there is a refrigerant line which goes through a heat cycle dispersing heating and thus providing cooling. Mini-split systems have proven to be flexible for zoning and retrofit applications since they have no ductwork, and so they avoid energy losses experienced in a typical central air system [17]. Depending on the size of home and type of ducts, energy losses for duct work can account for up to 20% to 40% [16], if ducts are accessible for re-sealing there is potential for gaining approximately half a ton of cooling [17]. A mini-split system has potential to decrease operational usage, thereby providing a substantial amount of energy savings compared to central air systems, and a cost benefit can be realized depending on the house and type of application. Initial capital costs of a mini-split system range in the industry between $1,500 to $2,000 per ton of cooling, this is approximately 30% more than the cost of a central AC system (excluding ductwork) [18]. Field measurements for cooling energy use will provide a direct comparison between zoned and central cooling systems.

An article by ASHRAE, “Emerging Technologies – Ductless Mini-Split Systems” [19], states that ductless mini-split systems can reduce HVAC energy consumption relative to ducted systems in three ways. Firstly, ducted systems avoid losses of conditioned energy via duct air leakage. Secondly, significant portions of ducts in uninsulated spaces such as attics or basements, lacking ample insulation can result in energy loss. Lastly, they only condition spaces on when occupied, where central systems can only achieve this by using dampers and variable air volume blowers. Studies of residential duct leakage only provide approximately 70% effective cooling. 24 houses in California were studied for cooling [20]; central air conditioning systems were replaced with zoned cooling systems and resulted in approximately 20% energy savings. Although the article has presented benefits for zone cooling systems, temperature and relative humidity have not been addressed and may provide further benefits between the two systems. This MRP has measured energy performance, temperature, and relative humidity during the study period to evaluate the overall benefits between the systems.

Room level zoning of forced air systems

A publication by the University of Virginia examines a field test to an existing one-storey seven room house of approximately 1400 square feet with a modified two-zone system forced air central system [20]. The study used sensors and timers to adjust an existing central HVAC system to a multi-zone system, over 20-day duration. The results showed that approximately 20% energy savings was achieved for the multi-zone forced air mechanical system compared to a single zone thermostat in the cooling mode for whole house air cooling. This was achieved by closing duct lines from certain un-used areas in the house, via automated dampers and booster fans. The study was only 20 days in duration and makes recommendations for longer studies to account for possible changes in weather. The comparative study has provided valuable insight on how modifications to central systems with a modified zone approach can reduce energy consumption; however the study has only been applied to a single storey house scenario. The subject MRP has a longer duration study over the summer of 2013 and investigated a three storey house for the effects of energy, temperature and relative humidity on a zoned and central AC system. The MRP also made use of energy model simulation to account for possible changes in weather and human occupancy which may have significant impacts on the results.

An article within ASHRAE involved field-testing to an energy efficient townhouse in Pittsburgh with a modified forced air cooling system [21]. The study focused on an unoccupied townhouse during a 48-hour period. System performance measured air temperature and space conditioning energy end use. Air distribution was divided into three zones and AC settings were limited to two stages; 50% and 100% system operation. The study found that the modified zoned system approach produced better thermal comfort on higher floor levels; consequently the system modifications resulted in more energy use by approximately 6%, due to the constant AC settings. The study found that the central system performed well on the first floor where the thermostat was located, but on the second and third floors there was a lack of airflow. Although the modified central AC system provided better thermal comfort, the increase in energy consumption from the reduced system setting is due to the lack of variable speeds with central AC compressor technology and fixed fan setting. It has the ability to fluctuate settings for fan and compressor speed, this results in overworking of the equipment to achieve the desired output. The study was limited to a 48 hour period; however the results are promising from a thermal comfort perspective on higher floor levels during the modified zoned AC system. This MRP is longer in study duration with three separate houses, system settings have less variability to allow for a more realistic house comparison. Temperature and relative humidity sensors were used to track conditions between floor levels in real time.

A zoned residential forced air system was tested in a NAHB laboratory house [22]. The test house consisted of five zones and with an unconditioned basement, a single speed blower, and single speed air conditioning unit. The test showed a 29% reduction in cooling energy use with zoning and temperature set point adjustments, as well as a dramatic improvement to thermal comfort. The report stated that zoned systems encourage energy conservation; however, zoning can cause higher operating costs if a thermostat setback is not used. Studies have demonstrated that a multi-zone system will use 35% more energy than a central thermostat system when a constant set point is used [23]. While there is an increase in energy consumption, a zone system does provide more uniform temperatures and better thermal comfort throughout the house than that offered by a central thermostat. The findings for multi-zone forced air systems have been promising for energy reductions, provided thermostat setback points are maintained. This MRP further evaluates a single zoned hydronic systems limited to the third floor of the RENO2050 house and compares with a whole central forced air systems; although there are no multi-zones or thermostat setbacks, a zoned system should provide improved thermal conditions as well as a reduction in energy.

Building Envelope

The building envelope plays a significant role for energy performance in buildings and in this field study. In order to compare energy use, building envelopes need to be classified according to their air tightness and thermal properties. "Building airtightness is one factor that affects building air change rates under normal conditions of weather and building operation. These air change rates account for a significant portion of space-conditioning load and affect occupant comfort, indoor air quality, and building durability" [24]. An ASHRAE study [25] had 43 test houses across the United States, which investigated temperature, relative humidity and mechanical equipment operations with sensors placed throughout the homes. Research was carried out between 2000 to 2005 over various Mid-West US states. Test houses had varying levels of building envelopes 1) Standard 2) Medium (Energy Star rated) 3) High Performance (Building America Standard) as well as various mechanical systems. The study found that space humidity level increases occurred when sensible cooling loads were modest, such as in the shoulder seasons (fall and spring) and during summer nights. For conventional cooling systems relative humidity was reasonably controlled within the 60% relative humidity range however in the shoulder seasons there were occurrences exceeding this range. For high performance homes, the study showed a need for dehumidification when cooling loads were modest which also enables other energy efficient improvements. The study was conducted over multiple U.S. states and thus results varied due to weather. This study does not report on energy measurements, which is a significant gap in this overall comparison. This MRP fills this gap by directly measuring and reporting on total cooling energy use during summer 2013.

A 170 house study in Finland was conducted to determine how the building fabric and natural ventilation affect indoor conditions [26]. The study was conducted all year round and measurements of temperature and relative humidity were recorded on houses with the following construction: timber, brick, concrete and autoclaved aerated concrete (AAC). The test houses did not have any air conditioning systems since the average summer temperature in Finland is only 21°C. The results concluded that the houses constructed of timber frames had higher daily swings in temperature and relative humidity compared to the brick, concrete and AAC houses, which were more thermally massive. Furthermore, it stated that the ventilation systems have the greatest capability to effect indoor climate conditions when compared to the building fabric. The report provided insight on the relationship between indoor thermal conditions and building envelope types, however the study was limited to houses where only natural ventilation was used. Energy use for cooling was not discussed in this report; however its findings can be applied to specific cases where only natural ventilation is needed in a space, such as in a zone cooling application where only certain spaces are cooled. This MRP addresses zone cooling and will investigate how indoor temperature and relative humidity change within the subject test houses. The temperature and relative humidity sensors across floor levels and other fieldwork provide the framework needed to measure the benefit of zone and central cooling.

The energy impacts of air tightness and ventilation levels on the existing U.S. building stock was investigated through a study from the University of Berkley [27]. The study used different computer energy modelling tools to assess the potential for improving air tightness levels, since higher airflow causes an increase in building energy usage. This study concluded that approximately 2.9 quads of energy could be saved annually if the entire U.S. building stock was upgraded to PassiveHouse standards and further estimates that $22 billion in annual energy savings can be achieved through these upgrades. Although an unreasonable feat to achieve, the study's conclusions are significant for the need for more air tight buildings. The study has covered multiple climatic zones and did not specifically address cooling energy performance in any of the results. The subject MRP attempts to fill the gap in the topic of cooling energy performance by comparing field results on three test houses that have varying levels of air tightness and different mechanical systems, from this the benefit of zone and central cooling can be compared.

The energy use on a ducted forced air central system and a ductless hydronic zoned system was compared by the Alliance for Residential Building Innovation (ARBI) [28]. "Hydronic distribution offers several advantages over traditional forced air systems, including reduced surface area of conduits (pipes vs. ducts), elimination of the need for duct chases, substitution of pumps for higher energy use fans, and more efficient zoning" [29]. Distribution efficiencies were reported to have 64% energy savings for a ½" diameter hydronic pipe with R-5 insulation compared to an 8" diameter air duct with R-8 insulation on the central system (Refer to Figure 4 below). The study also compared fan energy use on the central system to pump energy use for the hydronic. A typical forced air single blower consumed 365W for 1,000 cfm air conditioner, a hydronic system with a four zone two-pump system had 300W of energy use, approximately 18% energy savings was realized for the hydronic system. Computer simulation using TRNSYS software was used to model these systems; approximately 16% less energy for total cooling use on the hydronic system was achieved. There are superior results for the hydronic systems; however this has only been with computer simulation. Actual field validation has not been addressed in this study and has been stated as future work to measure in-situ performance. This MRP has added to the research in this area by obtaining field measurements for energy usage on both hydronic and central air systems over an entire summer period. The research also measured temperature and relative humidity across the houses for overall performance to determine the benefits between zone cooling and central air systems.

Figure 4: Air Duct vs. Hydronic Pipe.

Hydronic system use was investigated through the Building America program and U.S. Department of Energy [30]. Energy modelling using TRNSYS software with baseline cases for hydronic and forced air systems. Results from TRNSYS indicated that annual heating and cooling energy use (site and source) can reduce up to 22% when a forced air system is switched to a hydronic system. The 22% savings was attributable to the lower energy required by pumps and small fans vs. central air handler blowers, and reduced losses from pipes as compared to ducts. The report also addressed the effects of zoning hydronic systems when multiple heat pumps are added in a parallel sequence. Adding zoning to hydronic systems with multiple heat pumps is more effective than a zoned forced air system. Hydronic systems can accommodate a variable fluid velocity and pressure flow when fewer than all zones are operating and since the pressure in hydronic piping does not cause noise or leakage problems that are often associated with ducted central systems. TRNSYS modeling software was completed to determine how hydronic zoning would affect distribution efficiency. The MRP attempts to add to research work in this area by field testing houses for cooling energy use for an entire summer period in 2013. The field results from this MRP will also provide validation data that will be similar to the energy simulation used by the Building America program. The report identifies a lack of research in the area of field performance and validation since there is a heavy reliance on user operation which computer programs can only estimate using set schedules. This MRP will attempt to add to this area of research through actual field measurements on the houses for energy use, and real time data on temperature and relative humidity across houses. These results will facilitate a more representative comparison for a cooling energy study on three side-by-side houses.

The literature review has shown focus on the area of residential zoned cooling systems, central forced air cooling systems and residential building envelope studies. Generally, these studies focused on either energy use for zoned or central systems, building envelopes and temperature measurements, but seldom have all criteria been compared together. Where studies attempted to draw conclusions from all criteria, data was limited in duration or did not take into consideration external factors such as weather, human occupancy, and building constructions. Given the gaps in existing literature, this MRP seeks to contribute to the research area and to fill the gaps on the benefits between zone and central cooling systems. Field results from this study have a longer study duration over summer 2013. The variables in the field comparison of the three test houses is limited and more controlled since all house are in the same location, of similar vintage, size, orientation and have the same number of house occupants. Furthermore, the use of sensors to measure temperature and relative humidity in real time will assist the identify any performance benefits throughout the three level houses and the recording of energy use in real time can identify peak loads and total cooling energy use.

3.0 METHODOLOGY

This study involved measuring the performance of three side-by-side houses located in Toronto, Ontario. House A and B have been labelled as the pre-retrofit houses and the Reno2050 house is the post-retrofit house having recently undergone a deep energy renovation. Field measurements have been recorded over the summer between June to September 2013 [31].

3.1 ENERGY METER READINGS

Fieldwork was conducted to install devices that measured direct energy use from the air conditioning systems on each house. The devices used consist of a power meter with pulse output, setup directly to the AC power sources at each electrical panel. The power meter was connected to a pulse input data logger to record energy use at regular one minute intervals for the summer 2013 period that was from June 24 to September 11, 2013. Readings were logged in real time and data is presented in Section 6 of the report. As part of the study and to position cooling energy in the overall energy consumption pie for each house, the research gained access to each home's utility energy bills from 2012 to 2013.

3.2 ENERGY MODEL SIMULATION AND STUDY COMPARISON

In order to compare the results from the field study, energy simulation was used in an attempt to normalize the cooling energy use of each house according to building construction, weather and human occupancy. An existing baseline model from the Renovation2050 program was utilizied and modified for the purpose of this study using Energy Plus software [32]. (Refer to Figure 5). The baseline model was modified with a central forced air mechanical system as well as a zoned variable refrigerant cooling systems and the existing building envelope construction was also modified. Refer to Table 1 for four scenarios from the energy model. Refer to Figure 6 and 7 for a schematic elevation section of the Reno2050 house for both zoned and central systems [33,34].

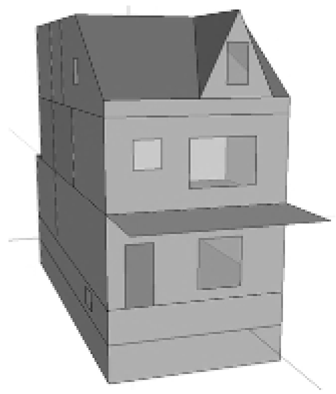


Figure 5: View of RENO2050 Model in EnergyPlus [32].

Table 1: Field Study and Energy Model Cases

Field Case 1: House A
Field Case 2: House B
Field Case 3: Reno2050
Model Case 1: Zoned System with Tight Envelope
Model Case 2: Zoned System with Leaky Envelope
Model Case 3: Central Forced Air System with Tight Envelope
Model Case 4: Central Forced Air System with Leaky Envelope

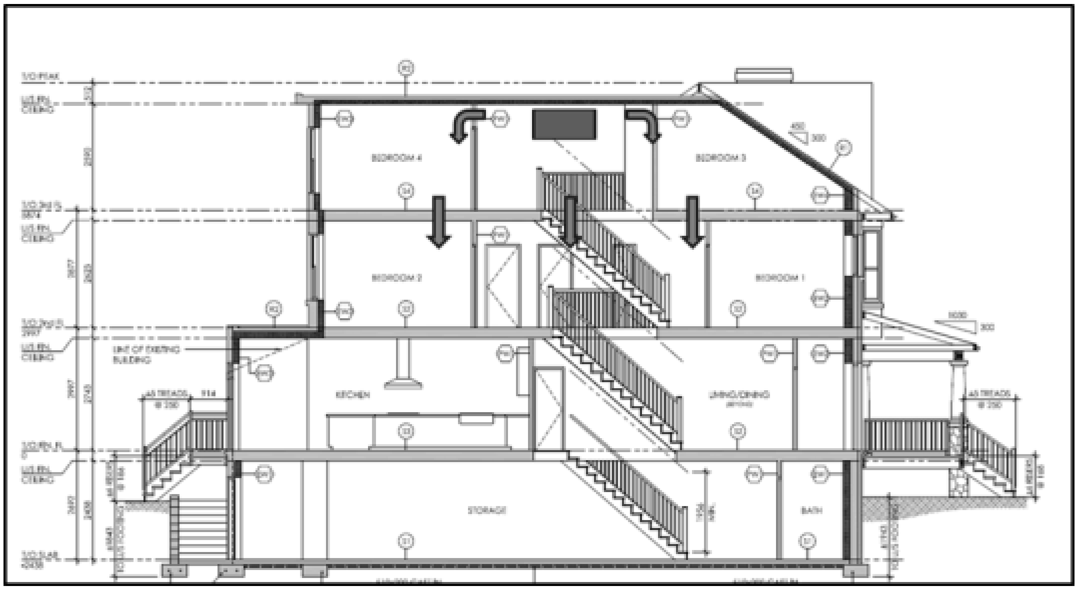


Figure 6: Schematic of zoned system in Energy Plus [33].

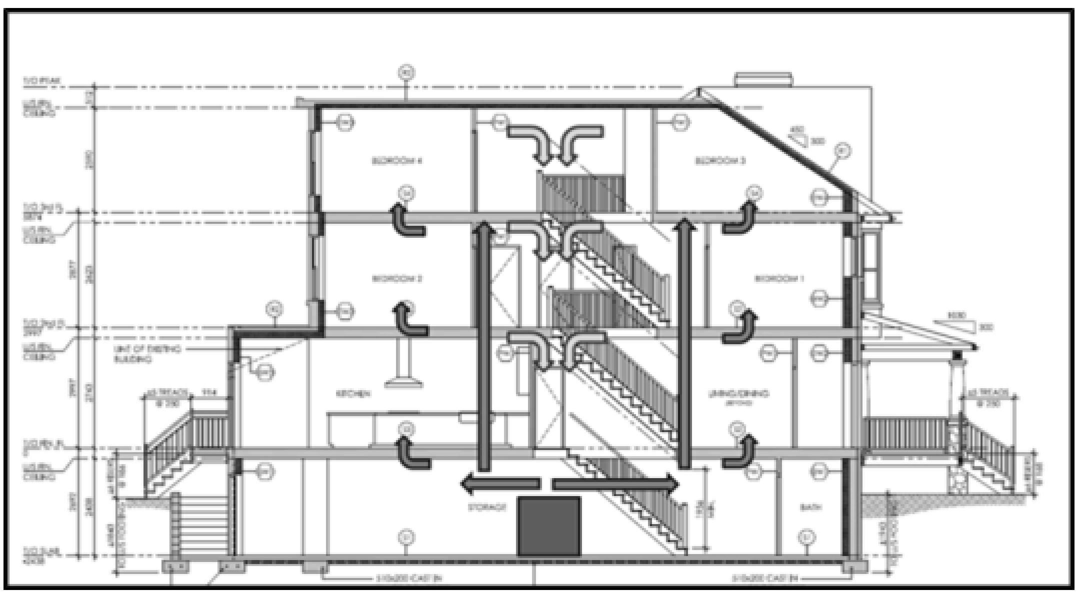


Figure 7: Schematic of central system in Energy Plus [33].

Weather for the energy simulation was calculated according to ASHRAE [2009] conditions for Toronto, Ontario and field results were normalized according to 2012-2013 weather data for Toronto (Refer to Figure 8) [33].

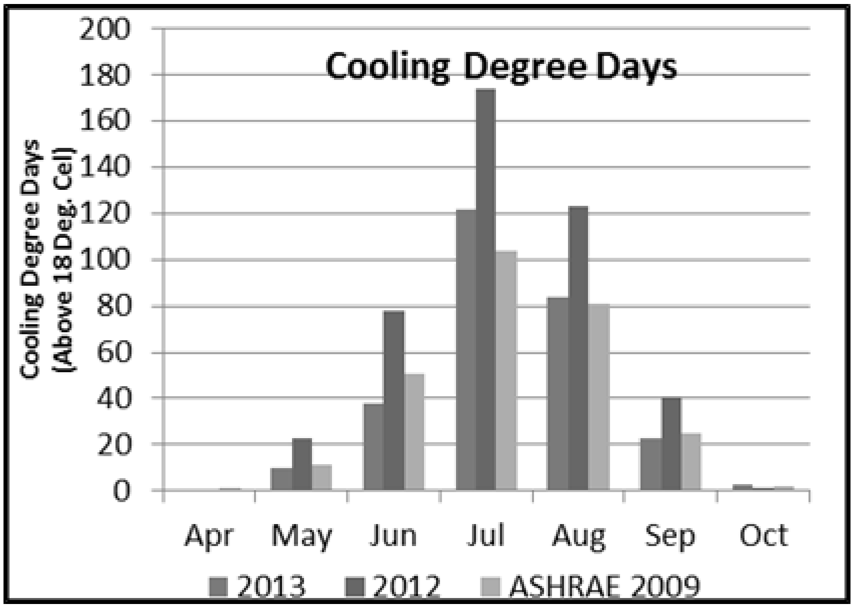


Figure 8: Cooling Degree Days for Study Comparison [35].

3.3 COMFORT MEASUREMENTS

The level of comfort within the test houses has been investigated during this study and includes temperature and relative humidity, which have been recorded during summer 2013 via remote sensors. The sensors recorded temperature and relative humidity in real-time from a web based remote monitoring solutions provider: OmniSense [36]. Sensor locations were previously established and installed as part of the Renovation 2050 program, and have been placed on all levels of the houses. Test House A and House B had eight individual sensors installed and the RENO2050 House had nine sensors. Refer to Table 2 for a list of sensor locations within each house.

Table 2: List of Sensor Locations in Test Houses

HOUSE A	**HOUSE B**	**RENO2050 HOUSE**
Basement South	Basement South	Basement
Basement North	Basement North	Basement Thermostat East
Main Floor North	Main Floor North	1st Floor Kitchen Entrance East
Main Floor South	Main Floor South	1st Floor Kitchen Island
2nd Floor North	2nd Floor North	1st Floor West
2nd Floor South	2nd Floor South	2nd Floor Stairwell East
3rd Floor North	3rd Floor North	2nd Floor Master bedroom
3rd Floor South	3rd Floor South	3rd Floor North Room East
		3rd Floor South Room East

4.0 FIELD STUDY PREPARATION: RENO2050 AND ADJACENT HOUSES

4.1 HOUSE DESCRIPTIONS

The site was located in Toronto, Ontario. Each house was located adjacent to each other, had similar orientation and construction vintage. A description of house constructions and mechanical system properties is listed below for House A, House B and Reno2050 House (Refer to Figure 9 and 10 and Table 3) [33,34,37].

HOUSE A **HOUSE B** **RENO2050 HOUSE**

Figure 9: Front view of Test Houses.

HOUSE A **HOUSE B** **RENO2050 HOUSE**

Figure 10: View of Air Conditioners for each test house.

Table 3: List of House Constructions and Mechanical Systems.

	HOUSE A	HOUSE B	RENO2050 HOUSE
Building Envelope			
Foundation Type	Triple Wythe Brick Masonry.	Triple Wythe Brick Masonry.	Triple Wythe Brick Masonry.
Roof Type	Sloped Asphalt shingle.	Sloped Asphalt shingle.	Sloped Metal Roof and Flat Modified Bitumen Roof.
Wall Type	Double Wythe Brick Masonry.	Double Wythe Brick Masonry.	Double Wythe Brick Masonry.
Wall Insulation	None (Cavity Wall with Lathe and Plaster).	None (Cavity Wall with Lathe and Plaster).	150mm (min.) 2lb Closed Cell Spray Applied Polyurethane Spray foam insulation.
Windows	Double pane with wood and aluminum frames.	Double pane with wood frames.	Fiberglass frames with effective quad glazed. IGU's.
Mechanical Systems			
Cooling Mode	Central Air Cooling. Whole house.	Central Air Cooling. Whole house.	Zoned mini-split. On third floor in conjunction with window airing.
Cooling System	Lennox HSXB15 SEER 13.6 [1]	ICG by Keeprite (SEER unknown)	Mitsubishi Mini-Split M-Series System SEER 26 [2]
Heating System	Forced air natural gas furnace.	Forced air natural gas furnace with electric baseboards on 3rd floor.	Radiant floor heating.
Cooling Thermostat Type and Location	Programmable, but not set back Summer. Located on main floor.	Programmable, but not set back in summer. Located on main floor.	On board mini-split unit

4.2 IN-HOUSE QUESTIONNAIRE

An In-house Questionnaire was distributed to all homeowners to document any known historical information on the houses and any other performance issues related to the cooling season (Refer to Appendix A). The questionnaire confirmed that Houses A and House B were considered to be in their original state (pre-retrofit condition) and the Reno2050 House has undergone a sustainable renovation. House A and House B both experience over-heating on the third floors during the summer months. The Reno2050 House has not reported any specific problems with respect to overheating (Refer to Table 4).

Table 4: Summary of In-House Questionnaire.

List of Questions	HOUSE A	HOUSE B	Reno2050 HOUSE
How many occupants live in the house?	4	4	4
How long have you lived in the house?	16	10	3
Approximate age of house?	105	112	110
Has there been a recent renovation to the house?	No	No	Fully renovated in 2010.
Age air conditioner?	9 years	20 years	3 years
Are there any stand-alone window unit air conditioners in any of the rooms?	No	No	No
Are there any areas of the house that are too hot?	3rd floor, particularly in the summer, especially near the skylight.	3rd Floor in the summer, or when temp reaches higher than 24°C.	Not usually.
Is your basement cooled?	No	No	No
Use of basement?	Storage	Storage and Living Space	Storage and Living Space
How is the air conditioner controlled?	Thermostat	Thermostat	Handheld Remote
Does your house have a programmable thermostat?	Yes, but kept at constant temperature	Yes (set backs used in winter)	7 heating zones each with thermostat (no set backs used)
What temperatures do you keep the house at?	Approximately 21°C, year round.	24 to 25°C in summer; 19-20 °C in winter	24-26°C summer; 20°C in winter

4.3 BLOWER DOOR TESTING

Blower Door Testing was performed to measure the air leakage rates on the test houses to classify the level of air tightness. The Blower Door test was performed on test Houses A and House B; Reno2050 was tested prior to this study and results have been made available for use [38]. Building envelope air leakage testing is a key component in this study since air tightness levels affect occupant comfort and space conditioning requirements. The results from this test have produced an air change rate value (ACH) to characterize the level of air tightness of the building envelope.

Blower Door Testing was performed in general accordance with ASTM E1827-11 Standard Test Methods for Determining Air tightness of Buildings Using an Orifice Blower Door [39]. The Retrotec2000 blower door was used as an orifice blower door for this test [40]. Blower door testing on House A and House B was completed on

October 11, 2013. The tests treated the houses as single zones and blower door testing was performed following the single point method. Site safety and setup guidelines were followed according to ASTM test E1827-11 prior to initiating the testing. The procedure used a variable speed fan to depressurize the house while measuring fan pressure and house pressure. Data was collected and is presented in Table 5 below. HOT 2000 software was used to calculate ACH and ELA for each house refer to Appendix C for this breakdown. (Refer to Figure 5 for a summary of results).

Table 5: Blower Door Testing Results

	House A	**House B**	**Reno2050 House**
ELA @ 10 Pa (cm^2)	1964	2866	358
ACH @ 50 Pa	7.18	10.56	1.4
Volumes (m^3)	700	700	670
Leakage Through Thermal Envelope ($L/s/m^2$)	0.34	0.5	0.06

5.0 RESULTS

5.1 ENERGY USAGE: FIELD RESULTS

Total cooling energy use which includes cooling and fan energy use during the study period is presented in Table 6 and Figure 11.

Table 6: Total Cooling Energy Use Comparison: June 24 to Sept 11, 2013.

House	Measured Energy Usage Total (kWh)	Air Leakage Rate (h^{-1} @50Pa)	Overall Thermal Envelope
House A	1816	7.2	RSI_{wall}: 0.88 RSI_{roof}: 2.64
House B	1320	10.5	RSI_{wall}: 0.88 RSI_{roof}: 2.64
RENO2050 House	69	1.4	RSI_{wall}: 7.0 RSI_{roof}: 8.8

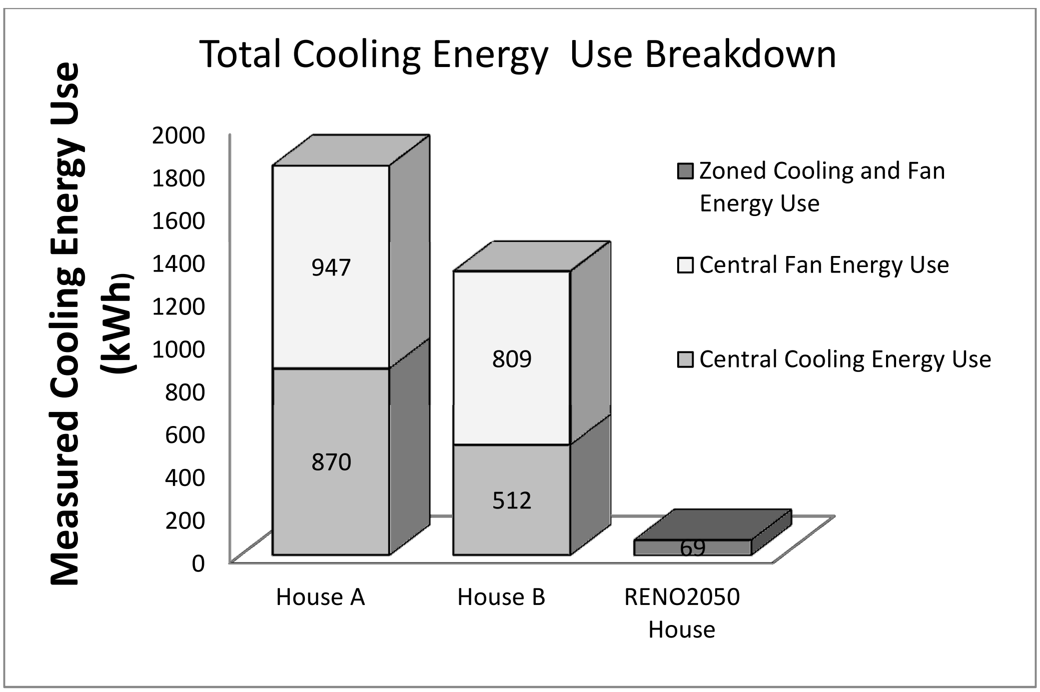


Figure 11: Total Cooling Energy Use Breakdown: Field Results.

Daily total cooling energy use during summer 2013 is shown for all three test houses in Figure 12. Results show that the Reno2050 house is the lowest consumer of energy over the evaluation period compared to Houses A and B. The total energy consumption results vary due to a cumulative effect of: (i) occupant behaviour, (ii) building envelope assembly difference, (iii) air tightness differences and (iv) cooling system type. It should be noted that the Reno2050 House was unoccupied during one of the cooling periods from July 13 to July 20, 2013. Based on Figure 12 below, the Reno2050 House only turns on three times during the summer period, whereas the level of use on House A and House B fluctuates over the study period.

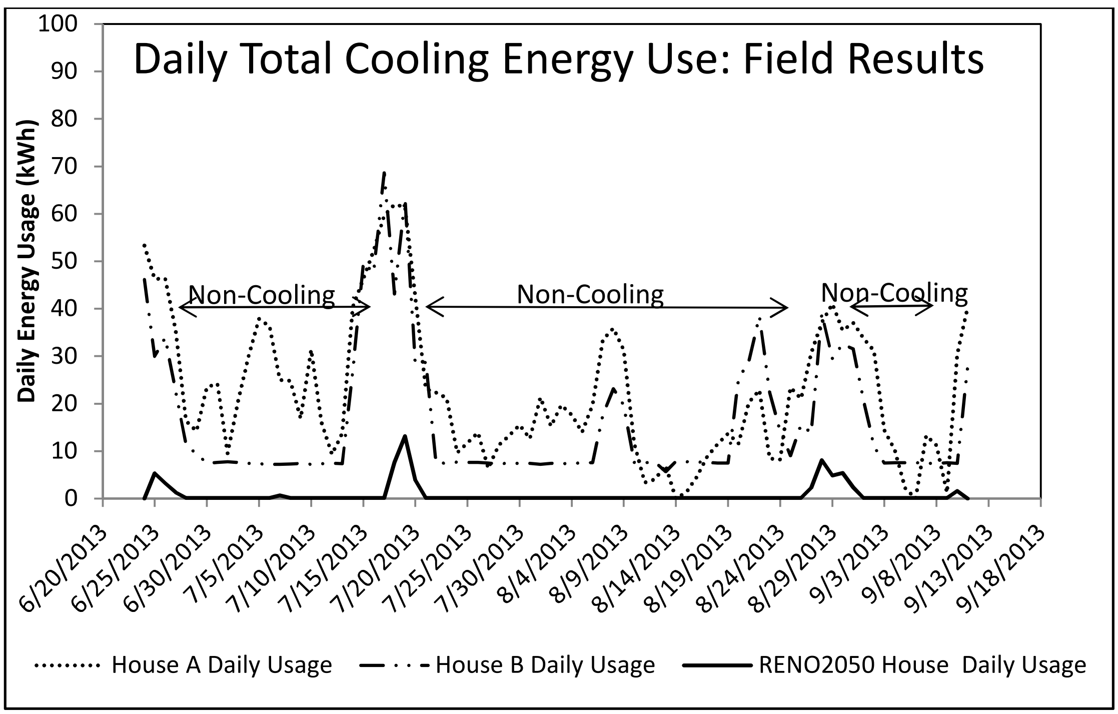


Figure 12: Measured Daily Total Cooling Energy Use.

An up close review of a 48 hour period during a peak summer day is shown in Figure 13 below; total cooling energy use was measured for each test house in one minute intervals. The field results show the varying levels of cooling energy consumption from equipment types. House A and B, both reach a constant cooling output at 40 W-h per minute and 60 W-h per minute respectively, while Reno2050 House reaches a maximum value of 20 W-h per minute and then decreases to a range of approximately 10 W-h per minute. Figure 13 shows how the central systems of House A and House B, reach a constant fixed level of cooling output, due to (i) the single speed fans and (ii) single speed cooling output from the rotary and scroll compressors on central AC equipment. The Reno2050 House has a variable level of consumption; this is due to (i) the multi-speed fan that is built into the unit and (ii) the inverter compressor which has a variable level of cooling output.

The level of operational use and frequency also varies during this 48 hour period. House A is in operation constantly over this period, while House B runs for the majority of the time but has several high frequency short cycles. The Reno2050 House only turns on once, while reaching a peak value and then decreases to a reduced setting. It should be noted that the Reno2050 House was unoccupied during this cooling period, however the cooling equipment was manually turned on during this time to keep overall temperature within a comfortable range.

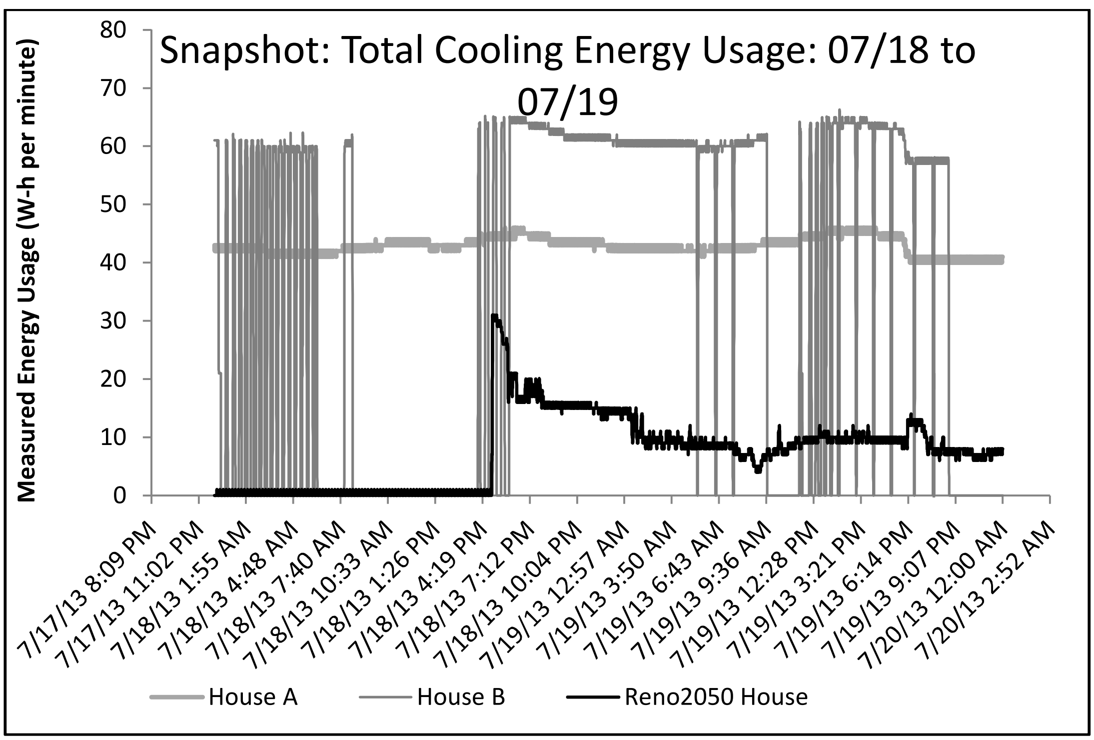


Figure 13: Snapshot of measured cooling energy usage.

UTILITY USAGE

Total household energy use data from utility bills in 2012 to 2013 were available during the study. An equivalent kWh use for energy has been presented in the results which have combined total gas and electricity energy use over the study period. An overall comparison between heating and cooling level consumptions is shown in Figure 14; all base load energy end use is included within this Figure. The 2012 summer was much hotter than 2013, as such there is increase in cooling use for both House A and House B, however Reno2050 House remains the same for 2012 and 2013.

A breakdown of energy use between natural gas and electricity consumption is shown in Figure 15 below. Electricity use is broken down further into total household electricity use and total cooling use; Figure 15 below indicates that cooling consumption for Houses A and B is approximately 14% and 13% of total electricity consumption respectively, and Reno2050 House consumes only 2%.

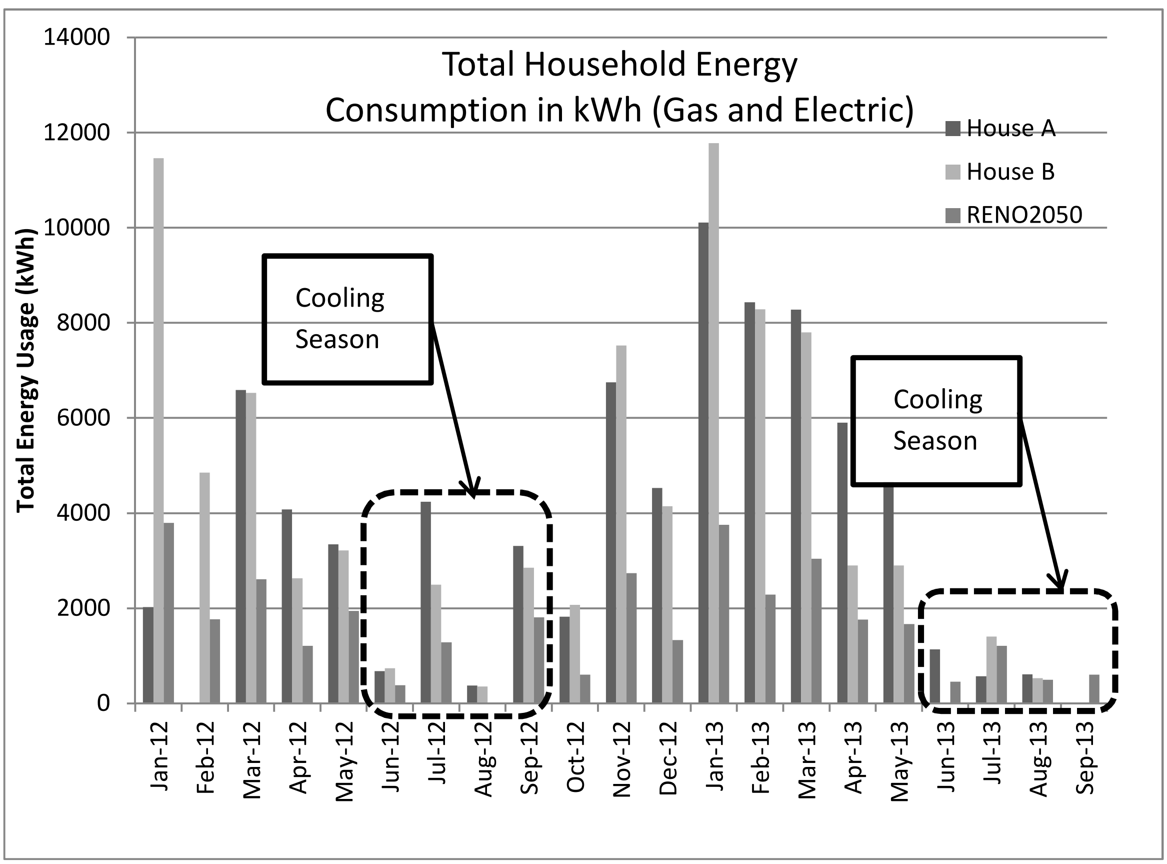


Figure 14: Total Household Energy Consumption 2012-2013 [42].

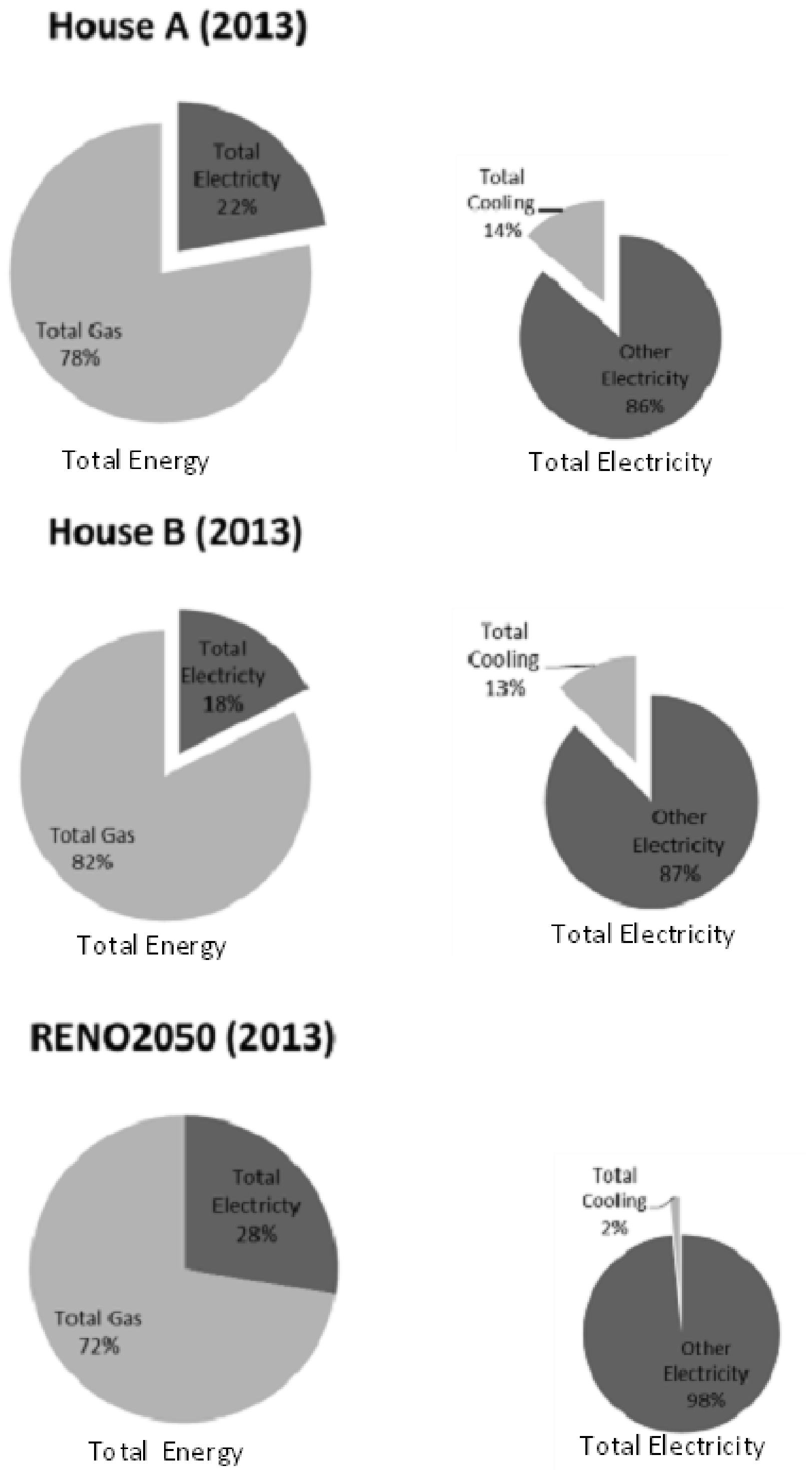


Figure 15: Breakdown of Energy Use for Houses A, B, and Reno2050 in 2013.

5.2 ENERGY SIMULATION AND FIELD STUDY COMPARISON

A description of the parameters used in the simulation with the Reno2050 baseline model is listed below in Table 7. Total cooling energy use from the models is presented in Figure 16; results from the field study are also included in this figure for comparison purposes. Results show that when the thermal envelope is upgraded and air tightness levels are tightened in zoned system cases 3 to 1; there is a decrease in energy use of approximately 66%. Similarly, when the thermal envelope is upgraded and air tightness levels are tightened for central system cases 4 to 2; there is a decrease in energy use of approximately 61%. Fan energy use is also a significant consumer of energy in cases 2 and 4; consuming approximately 63% and 49% energy use respectively. Therefore the energy models show that when a high performance building envelope is used, there are energy savings for both zoned and central systems.

The field study results included in Figure 16 show how energy use between real life conditions and energy simulation vary between the system types. The Reno2050 House consumes 60% less energy than its counterpart energy model Case 1, and Houses A and B consume approximately 50% more energy than its counterpart energy model Case 4. This comparison shows how factors such as equipment type and level of use have a significant effect on overall energy consumption. It should also be noted that the field study results are based summer 2013 weather season, and energy models are based on ASHRAE 2009 weather files for Toronto climate, consumption between weather seasons will be discussed further in the discussion Section 6.

Table 7: Description of Zoned and Central Systems for Energy Model.

Description	Zoned System	Forced Air Central System
System Description	1 Mini-split system for the third floor.	Forced air central system for whole house.
System Size	Auto size to third floor. Variable Refrigerant Flow.	Auto size to whole house. Single speed DX cooling coil.
Thermostat Location	Third Floor	Living Room
Cooling Set points and Schedule	For: All days Until: 24:00, 24.0°C	For: All days Until: 24:00, 24.0°C
Fan Schedule	No Fan	For: All days Until: 24:00, 24.0°C
Infiltration Rates		
Tight Envelope	Case 1: 1.4 ACH @ 50Pa	Case 2: 1.4 ACH @ 50Pa
Leaky Envelope	Case 3: 10.5 ACH @ 50Pa	Case 4: 10.5 ACH @ 50Pa

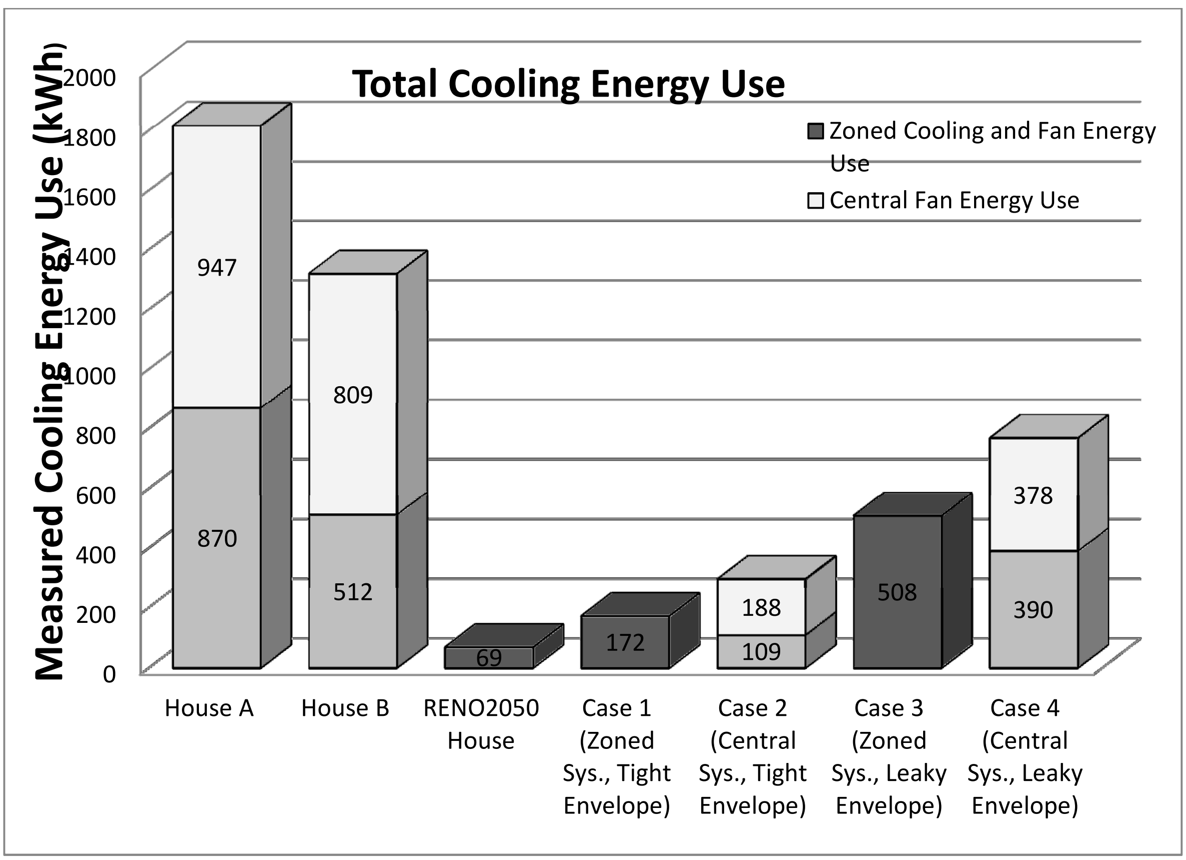


Figure 16: Total Cooling Energy Use: Energy Models.

Figures 17 and 18 show the correlation between daily total cooling energy use and cooling degree days for both the field results and energy models. Although the comparisons is for different weather loads, the consumption from the field results in Figure 17 shows the real life condition and the variation in user level and occupant habits, while the energy models in Figure 18 have a set schedule with less fluctuation in energy usage due to the controlled schedules set out in the simulation.

Figure 17 also shows how user behaviour affects the field study results. The periods between August 5 to 12 and August 19 to 26, had both central systems of Houses A and B in operation, however the zoned system in the Reno2050 does not turn on.

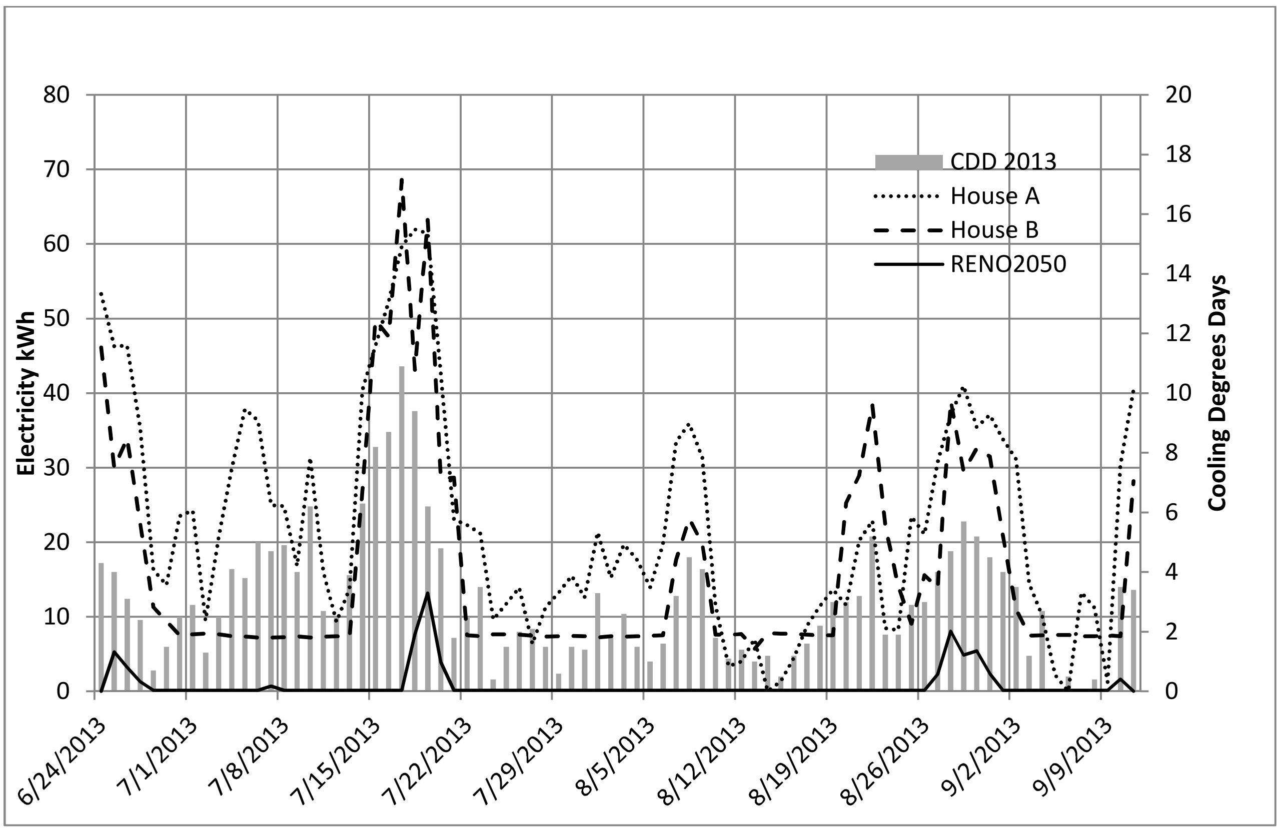


Figure 17: Daily Total Cooling Energy Usage vs. Cooling Degree Days: Field Results.

Figure 18 below shows a more controlled run time usage due to the fixed schedules setout in the simulation. All four model cases generally turn on at the same time, althought they all reach different levels of energy consumption to their mechaanical system and building envelope properties.

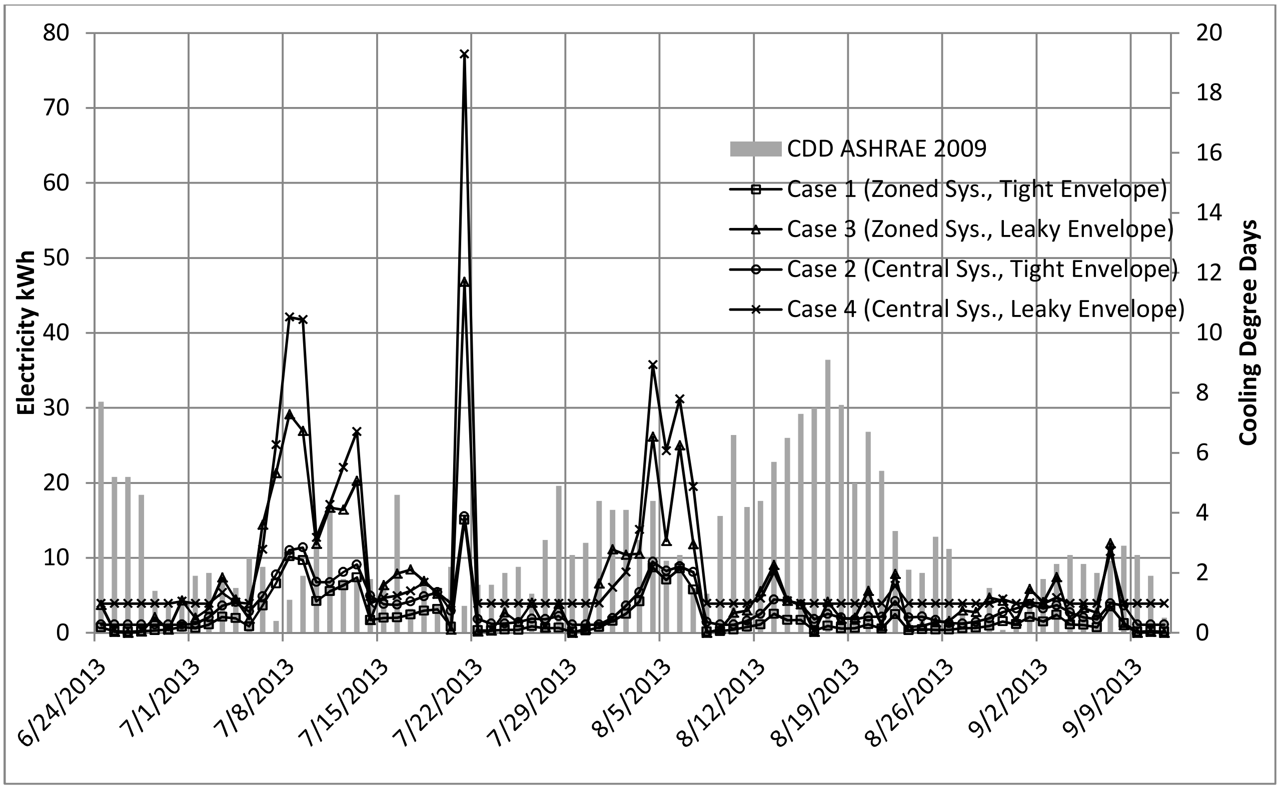


Figure 18: Daily Total Cooling Energy Usage vs. Cooling Degree Days: Energy Models

5.3 COMFORT RESULTS

The mean whole house temperatures and standard deviation of floor level temperatures has been presented in Table 8. The average whole house temperatures are all close in range, however the standard deviation of temperature varies across each floor level, and the highest deviation is on the third floor with respect to House A and House B. The Reno2050 House has the least temperature fluctuation between floor levels revealing further benefits associated directly with a high thermal resistance and air-tight envelope.

Table 8: Mean and Standard Deviation of House Temperatures.

	Mean Temperature (°C)	Standard Deviation Across Average Floor Temperatures Levels (°C)	Mean Temperature (°C)	
House A	22.4	2.85	Floor 1	21.3
			Floor 2	22.1
			Floor 3	26.4
House B	22.4	1.84	Floor 1	23.0
			Floor 2	22.9
			Floor 3	26.4
Reno2050 House	22.8	0.68	Floor 1	24.2
			Floor 2	23.4
			Floor 3	23.2
Exterior Temp	21.2	-	-	

Recordings on hourly temperature and relative humidity across the summer period have been presented in this Section; results are from hourly readings from the remote sensors and are reported on a per floor level basis (Refer to Figures 19 to 24). Additional notes on floor level temperatures are as follows:

- House A, has experienced a range of temperatures between 17°C to 32°C with standard deviation of 2.85°C. Floor level averages for temperature show that the third floor remains hotter than the rest of the house, by approximately 10°C. The first and second floor level temperatures are closer with each other and the basement level generally remains the coldest.

House A, has experienced a range in relative humidity between 55% to 70%, except on the 3rd floor which ranges between 40% to 50%.

- House B, has experienced a range of temperatures between 18°C to 35°C with standard deviation of 1.84°C. Floor level averages for temperature show that the third floor remains hotter than the rest of the house by approximately 5°C. The first and second floor levels are closer with each other and the basement level generally remains the coldest. House B, has experienced a range in relative humidity between 45% to 75%.
- Reno2050 House, has experienced a range of temperatures between 20°C to 30°C with standard deviation of 0.68°C. Floor level averages for temperature show all floor levels are close with each other, with a differential of approximately 3-5°C. Reno2050 House, has experienced a range in relative humidity between 55% to 80%.
- Daily average whole house temperature for the three test houses are all close in range for the study duration.
- Overall the relative humidity within all the houses fluctuate, although no trends have been noted. The fluctuations are due to indoor and outdoor factors with the environments, and there is no progressive accumulation on relative humidity levels.

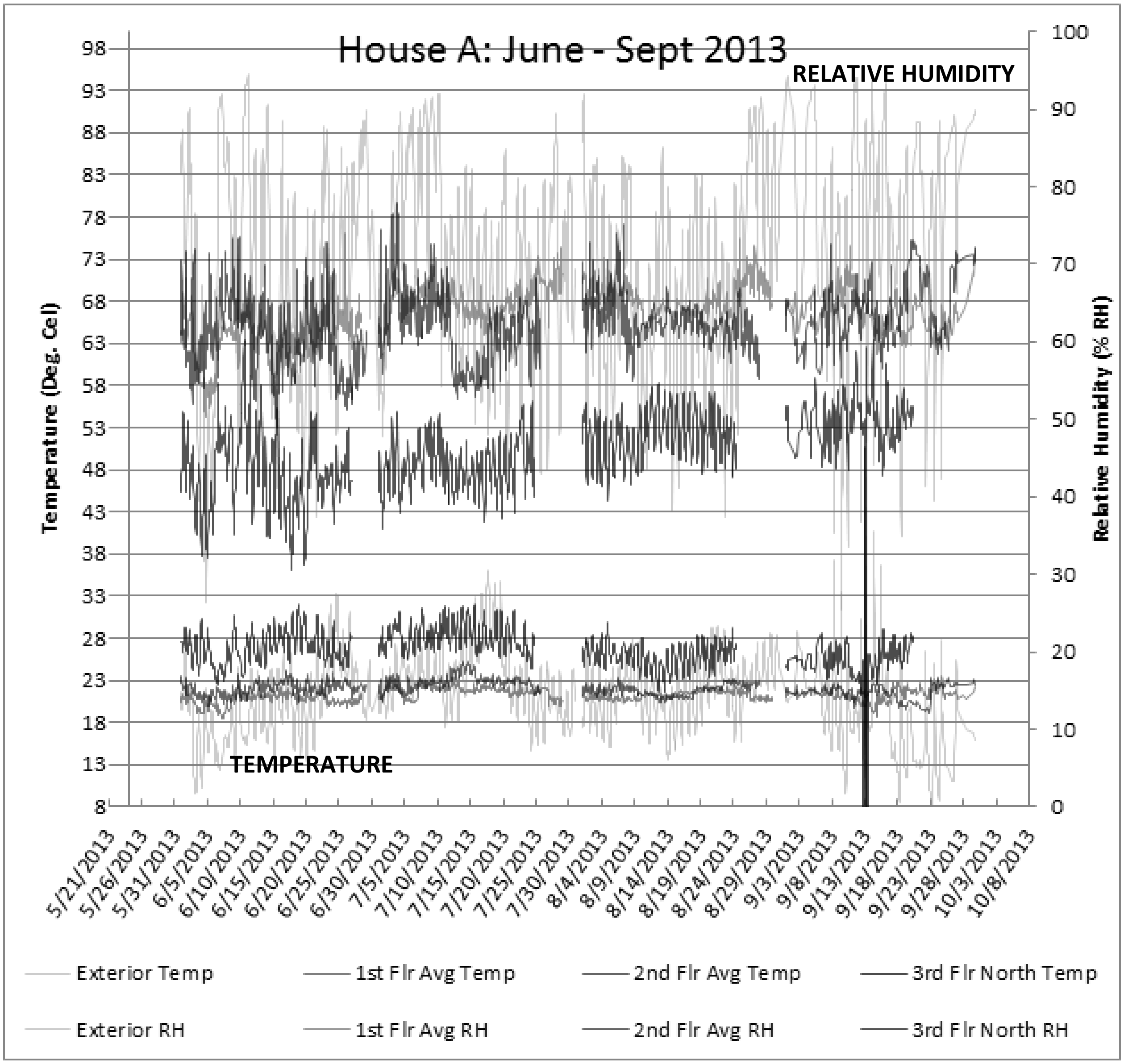


Figure 19: House A Average Temperature and Relative Humidity across various floor levels

Temperature Trends:	3rd floor temperature is generally the highest throughout the summer and fluctuates with exterior temperature. 1st and 2nd floors below floor temperatures.
Relative Humidity Trends:	All change with exterior temperature. 3rd floor has the lowest relative humidity.

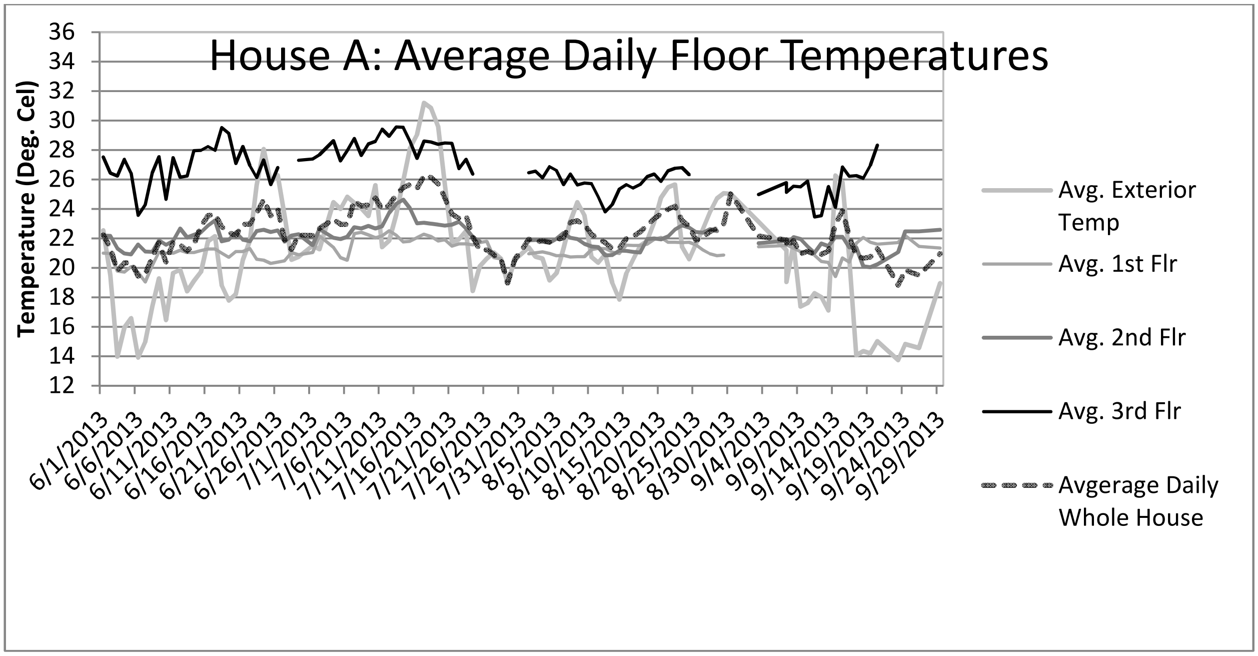


Figure 20: House A Average Floor level temperatures June to September 2013.

Temperature Trends: 3rd floor temperature is generally the highest throughout the summer and fluctuates with exterior temperature. 1st and 2nd floors are below 3rd floor temperatures.

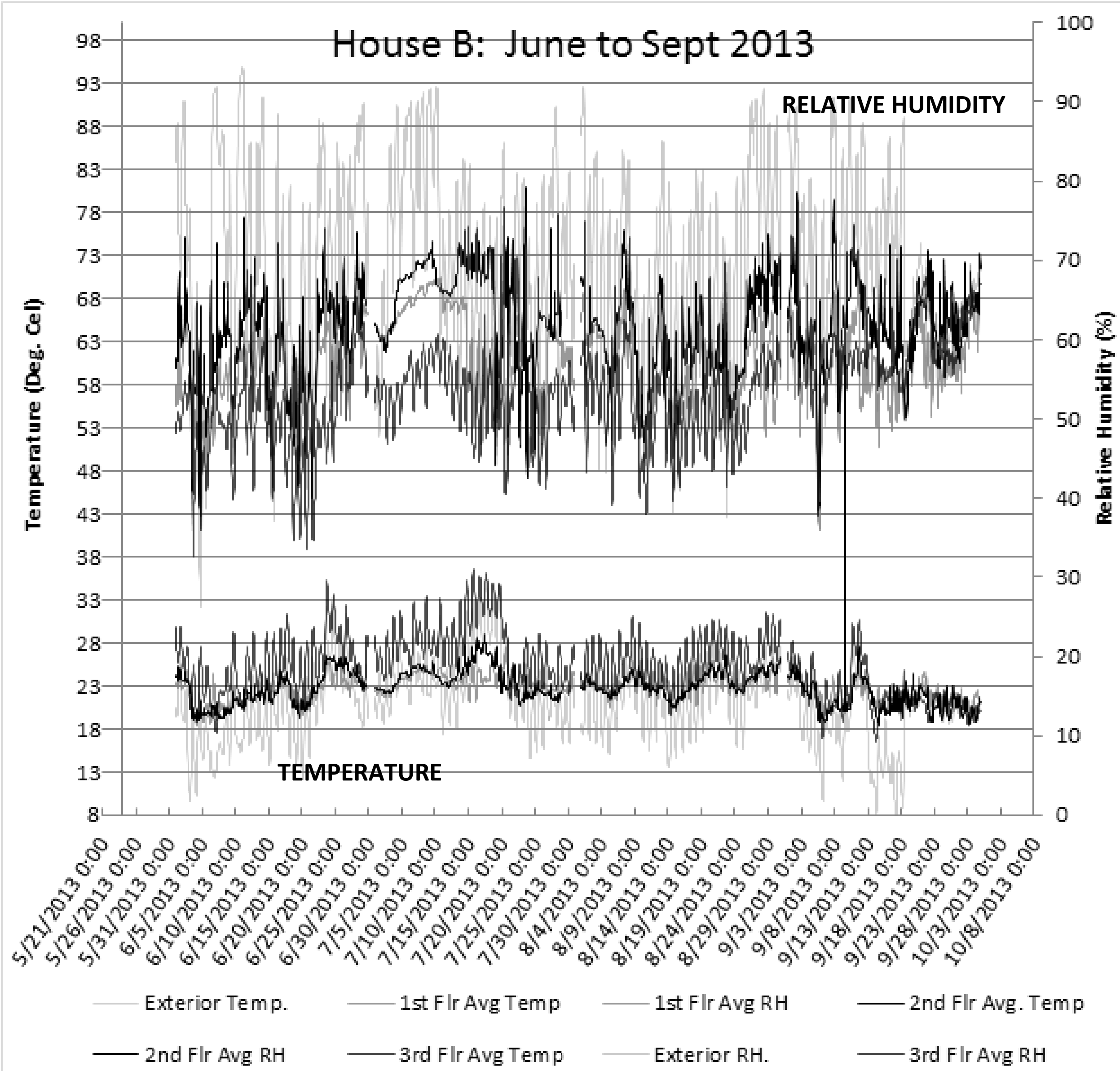


Figure 21: House B Average Temperature and Relative Humidity across various floor levels

Temperature Trends: 3rd floor temperature is generally the highest throughout the summer and fluctuates with exterior temperature. 1st and 2nd floors are below 3rd floor temperatures.

Relative Humidity: All swing with exterior temperature. 3rd floor has the lowest relative humidity.

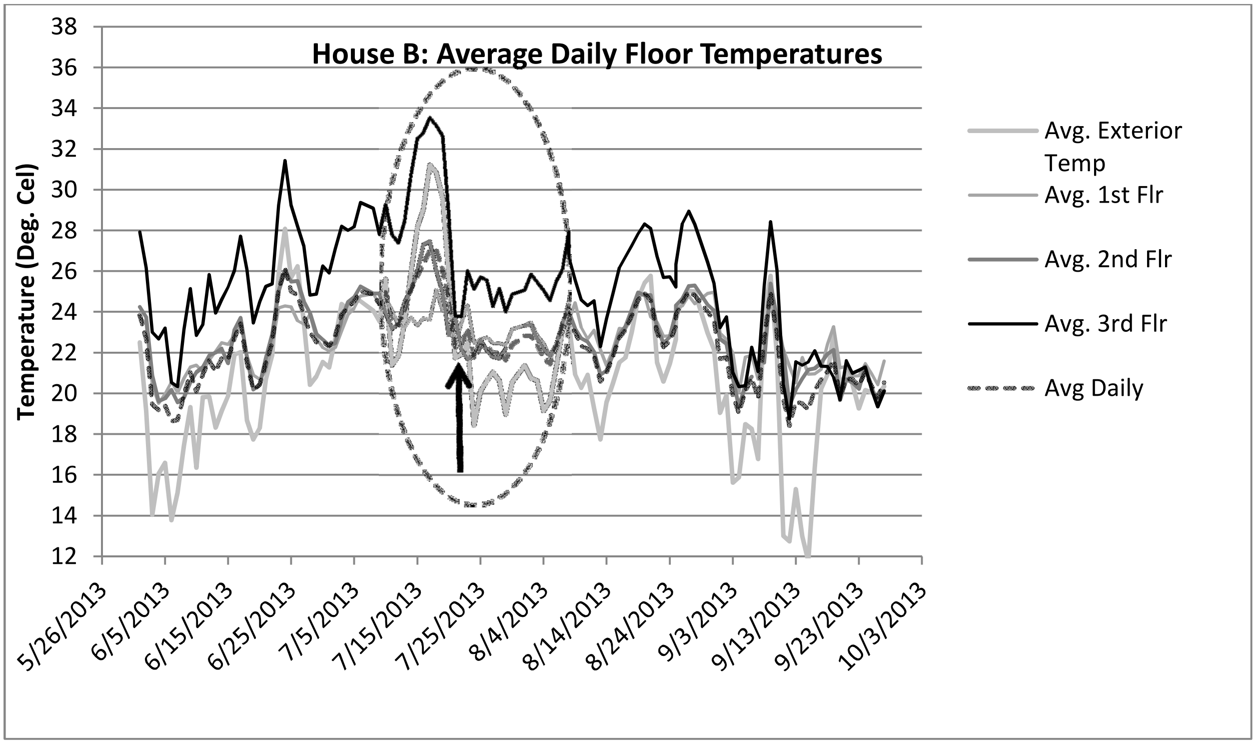


Figure 22: House B Average Floor level temperatures June to September 2013.

Temperature Trends: 3rd floor temperature is generally the highest throughout the summer and fluctuates with exterior temperature. 1st and 2nd floors are in below 3rd floor and have the most constant profile.
Average floor level temperature is approximately in between the maximum and minimum values.

The hatched oval and arrow on Figure 22, indicate a period where the AC system turns which results in a temperture drop across all floor levels. This behaviour will be discussed further in the discussion section.

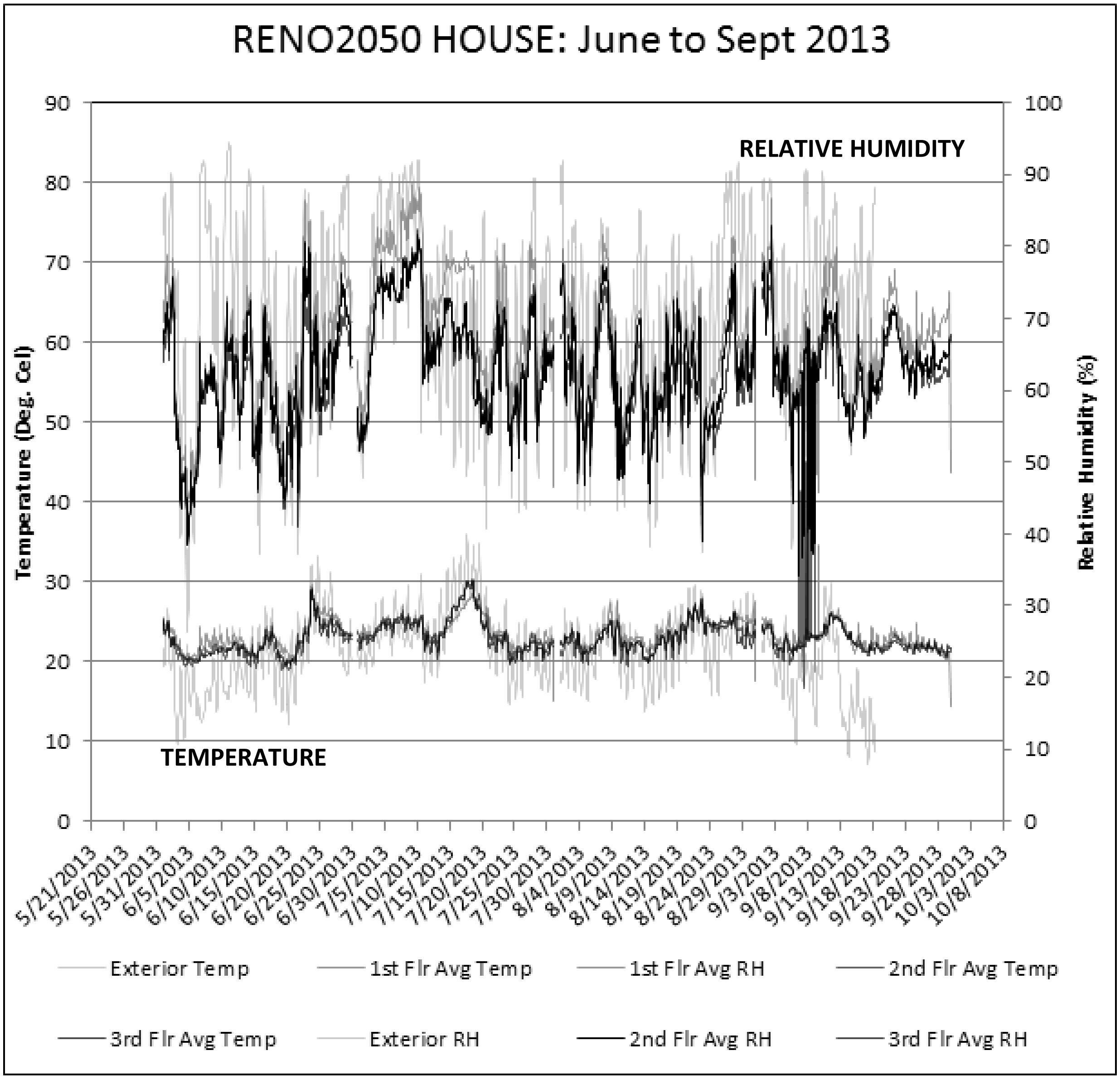


Figure 23: Reno2050 House Average Temperature and Relative Humidity across various floor levels.

Temperature Trend:	All floors levels are generally close with each other. A more constant average floor tempeature is shown.
Relative Humidity Trend:	Relative humidity fluctuares with exterior temperature.

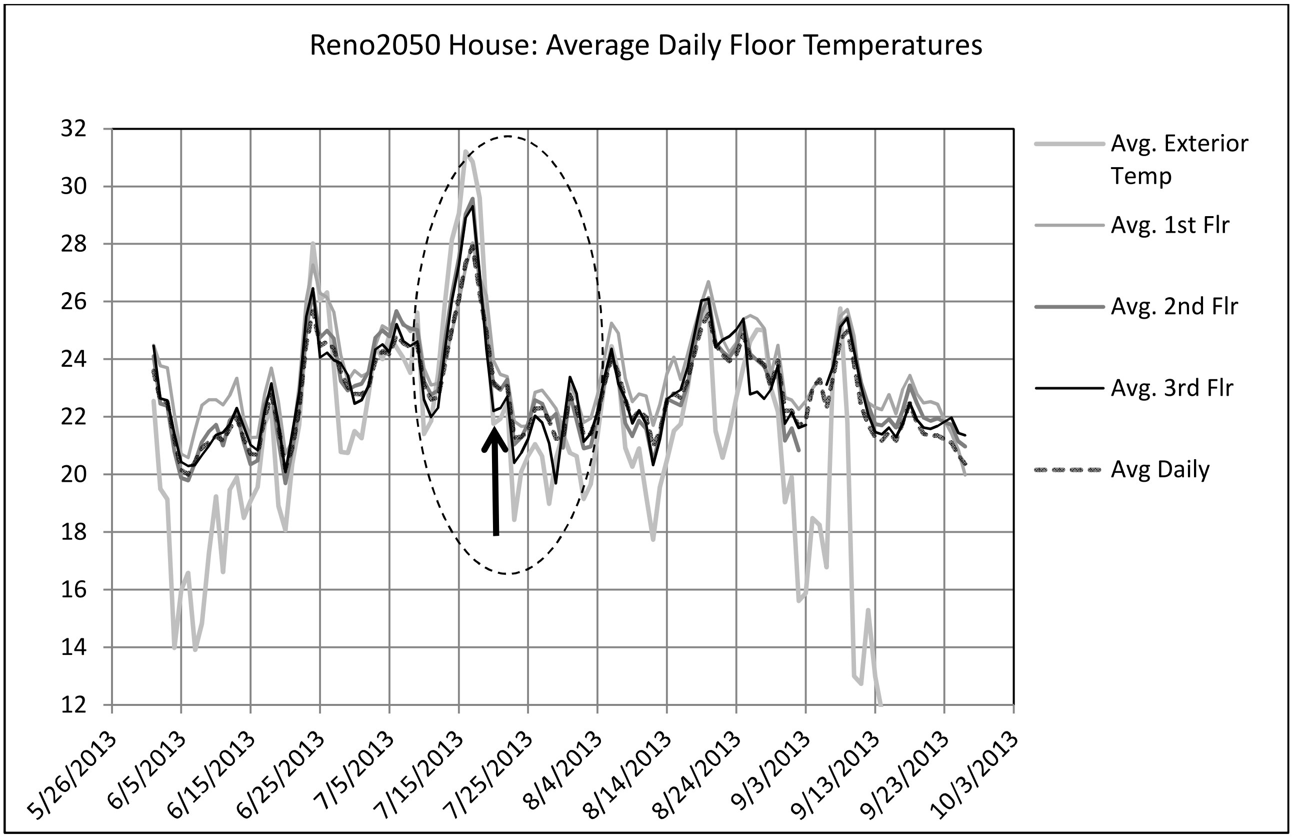


Figure 24: Reno2050 House Average Floor level temperatures June to September 2013.

Temperature Trend: All floors levels are generally close with each other. A more constant average floor tempeature is shown.

The hatched oval and arrow on Figure 24, indicate a period where the AC system turns which results in a temperture drop across all floor levels. This behaviour will be discussed further in the discussion section.

6.0 DISCUSSION

This section has been organized based on energy use and comfort results from section 5. The results have shown potential for energy benefits due to several factors, each of which will be discussed further in this section and include the following: (i) building envelope air tightness, (ii) equipment type, (iii) user type, (iv) schedules, (v) weather, and (vi) comfort. The goals for discussing these individual factors, is to understand where the potential energy benefits lie and to determine what impact they have had on energy use, where possible these factors will be ranked and quantified in order to determine their overall contribution to this study.

6.1 ENERGY USAGE

The Reno2050 house consumes approximately 96% to 94% less total cooling energy than Houses A and B respectively. The intent of this section is to discuss the main factors from the results which contribute to the energy benefits, including the following: (i) building envelope air tightness, (ii) equipment type, (iii) user type, (iv) schedules, and (v) weather.

6.1.1. BUILDING ENVELOPE AIR TIGHTNESS

Field results have shown the combination of a zoned system, tight building envelope, increased thermal resistance and particular user behaviour uses significantly less energy than houses with central systems, a leaky envelope, less thermal resistance and varied user behaviour. The level of air tightness of the building envelope contributes to this variation as well as other factors presented in following Sections. Multiple energy model cases were simulated to determine how the variation in building envelope air tightness affects overall cooling energy usage; while other variables such as schedule and level of use were kept constant.

Results from Figure 16 show that when the thermal envelope is upgraded and air tightness levels are tightened in zoned system cases 3 to 1; there is a decrease in energy use of approximately 66%. Similarly, when the thermal envelope is upgraded and air tightness levels are tightened for central system cases 4 to 2; there is a decrease in energy use of approximately 61%. Figure 16 also shows how fan energy use is also a significant consumer of energy in cases 2 and 4; consuming approximately 63% and 49% of total cooling energy use respectively. The energy models used a high performance building envelope which consisted of air tightness levels of 1.4 ACH @ 50Pa, and thermal envelopes of RSI_{roof} 8.8, and RSI_{wall} 7.0. The leaky building envelope cases consisted of air tightness levels of 10 ACH @ 50Pa, and thermal envelopes of RSI_{roof} 2.64 and RSI_{wall} 0.88. Fenestration levels were kept constant during the model cases and were not accounted for as it was outside the scope of this study.

From the field results, there is approximately 95% cooling energy savings for the Reno2050 house compared to Houses A and B, and based on the energy models approximately 60% energy savings is realized when the building envelope air tightness and thermal envelope is upgraded. Therefore the building envelope air tightness and thermal resistance upgrade is considered the most significant factor in reducing cooling energy use during this field study, while there are other factors that are significant they will be discussed in the next sections.

6.1.2. EQUIPMENT TYPE

Equipment type has also shown to be a significant contributor to energy use over the study period. An up close review of a 48 hour period during a peak summer day is shown in Figure 13. The field results show the varying levels of cooling energy consumption from equipment types. Houses A and B, both reach a constant cooling output at 40 W-h per minute and 60 W-h per minute respectively, while Reno2050 House reaches a maximum value of 20 W-h per minute and then decreases to a range of approximately 10 W-h per minute. Figure 13 shows how the central systems of House A and House B, reach a constant fixed level of cooling output, due to (i) the single speed fans and (ii) single speed cooling output from the rotary and scroll compressor technology on central AC equipment. The Reno2050 House has a variable level of consumption; this is due to (i) the multi-speed fan that is built into the unit and (ii) the inverter compressor which has capacity to achieve a variable level of cooling output. Therefore the equipment type of each unit has varied and has potential to affect the results; however the level of use during operation can also affect results over the study duration, refer to the next section on discussion of user type.

Equipment age between central AC systems was also noted to have an effect on the results. The cooling equipment in House B (20 years old, 60 W-h per minute) is consuming 33% more energy than the equipment in House A (9 years old, 40 W-h per minute), due to inefficiencies with older AC technology (Refer to Figure 13). The Reno2050 house consumed energy at a variable rate; a maximum value of 20 W-h per minute was first reached upon initial cooling period peak conditions (likely to deal with both a high latent and sensible load) and later decreased to an average of 10 W-h per minute (likely dealing with a predominant sensible load). Equipment age was another variable in this study that has affected the results on the central system cases.

6.1.3. USER TYPE

All three houses had the same number of occupants during the study period. Based on the field results in Figure 12, Reno2050 house is considered a light user of cooling energy, while Houses A and B are considered heavy users. The Reno2050 House turns on only three times during the entire study period of summer 2013. The usage of Houses A and B vary, there are periods where they both turn on and the Reno2050 house does not which includes August 5 to 12 and August 19 to 26. The level of use between House A and B is also shown during the up close review period over 48 hours per Figure 13.

House A is running constantly over this 48 hour period, and House B runs periodically with several recurring short cycles.

House B also uses constant fan energy throughout the study period, even when no cooling is provided, a flat line level of use of approximately 10 W-h per minute is maintained (Refer to Figure 13), and during the same period Reno2050 house does not use any cooling at all. The average floor level temperatures across these periods can be compared based on Figures 22 and 24, which indicate high 3rd floor level air temperatures and stratification effects while the Reno2050 house, without any cooling or fan use, has a constant temperature profile across all floor levels. The run time usage of fan energy alone for House B has not been effective in reducing air stratification effects. Further discussion on comfort and temperature variation will be presented in Section 6.2.

The energy model and field study results included in Figure 16 show how energy use between real life conditions and energy simulation vary. When the energy models are compared to field results, the Reno2050 House consumes approximately 60% less energy than its counterpart energy model Case 1, and Houses A and B consume approximately 50% more energy than its counterpart energy model Case 4. This comparison shows how the level of use has a significant effect on overall energy consumption and the differences between real life conditions and energy models.

6.1.4. SCHEDULES

Results have shown that equipment schedules had an impact on total cooling energy usage. Thermostats for Houses A and B were located on the main floor; House A had a set point of 21°C constantly throughout the summer and House B between 24°C to 25°C. Reno2050 House had cooling equipment operated by handheld remote with temperature setbacks of 26°C. The schedules for the energy models were set at 24°C for all days; the thermostat set point was on the third floor for the zoned system and on the main floor for the central system. The Reno2050 House, a light user of energy, consumed 69 kWh of energy whereas its counterpart energy model (case 1) consumed 172 kWh over the same period per Figure 16; both contain a high performance building envelope. In this situation, the energy model consumed more energy than the real life condition, which is due to the fixed schedule set out in the simulation.

Houses A and B, heavy users of energy, consumed 1817 kWh and 1312 kWh of energy and its counterpart energy model (case 4) consumed 768 kWh per Figure 16, both have a leaky building envelope. In this situation, the real life condition of the central systems consumed more than the energy models. Results have shown the zoned system was underused during the field study compared to the energy simulation, and the central system was overused compared to the energy simulation. There may be other possible effects to the large increase in energy use for central systems of Houses A and B, which may include: (i) air duct leakage, and (ii) improperly design duct work and lack of air balancing resulting in system short circuiting.

6.1.5 WEATHER

Energy models were simulated according to ASHRAE 2009 weather file for the Toronto area, and field results to 2013 summer from on-site measurements at the Reno2050 site. When the two summer seasons are compared, 2013 had 280 Cooling Degree Days (CDD) and ASHRAE 2009 had 275 CDD, which are recorded when the temperature exceeds 18°C. Thus summer seasons have been close in range and likely had limited effects on variations in the results. A review of the energy bills over 2012 and 2013 also show that during the hotter 2012 season (441 CDD), there was more variation in cooling energy consumption between House A and House B than the Reno2050 House. Figure 14 and 15 also show the level of energy use over this period per the energy bills record.

6.2 COMFORT BENEFITS

This section will discuss the comfort benefits during the study period, it will make reference to temperature and relative humidity Figures 19 to 24. The variation in comfort is seen throughout the study; during instances of all houses in cooling mode and when some houses are not in cooling at all (Reno 2050). The Reno2050 House only cooled on three occasions and was in a state of non-cooling for the majority of the study (i.e. relying on the high performance envelope in combinations with solar shading and natural ventilation, when applicable); Houses A and B have been in a state of cooling longer then the Reno2050 house. Temperature readings across all houses have varied, although the mean values across the houses are all very close in range. The standard deviation of floor level temperatures is highest at Houses A and B, 2.85°C and 1.84°C respectively, and thus has a greater degree of temperature swing due to their leaky envelopes than that of the Reno2050 House, 0.68°C standard deviation, with the high performance building envelope. Furthermore, the average 3rd floor level temperatues for both House A and B was 26.4°C, and Reno2050 House was 23.2°C.

During July 13 to 20, 2013, Figure 22 and 24 have been circled, the mechanical systems of both Houses B and Reno2050 turn on at approximately the same time. The rise and fall of the 3rd floor level temperatures have been noted, before and after the AC systems turn on. Figures 22 and 24, show that cooling is provided in both scenarios based on the temperature drop, however the 3rd floor of the Reno2050 House provides cooling to the 3rd floor level within 3 hours of operation while cooling is provided in House B approxiamtely 18 hours after operation. After a temperature drop is reached from this period of cooling, the Reno2050's 3rd floor temperatures remain cooler and more constant, while House B temperatures begin to incease to a higher temperature, the leaky building envelope in House B contributes to this increase while the high performance envelope of Reno2050 house maintains a constant temperature within the house.

7. FURTHER RESEARCH

The results of this study have been significant for quantifying energy use and performance differences between zoned and central systems. However, this is just a stepping stone for further research in this area. Longer study periods to validate the data over multiple summer seasons and over full year cycles to determine the overall net benefit of zoned systems and central systems for a Canadian cold climate can be performed. In addition to heating, the mechanical systems should also investigate how ventilation affects the systems. Future work could investigate ventilation rates with the use of tracer gas studies and the effects of air stratification at third floor levels. Further study should also look at measuring the real air change rates in the houses due to window airing. This was not measured in the study and would provide a better understanding on how the indoor conditions of temperature and relative humidity react during periods of natural ventilation from outdoor air. Operational use has also had a significant effect on total cooling energy consumption. Further research could investigate the benefits of thermostat setbacks as well as classifying level of use which could provide additional support to this research area.

More detailed energy simulation could also be performed to parse out and quantify the contribution of each driving factor affecting energy use and comfort. More controlled studies could also be undertaken to document multiple cooling seasons and to further quantify user behaviour and level of occupancy during the study periods.

8. CONCLUSIONS

The study has shown that there lies potential for energy benefits for zone cooling systems compared to central systems. These results depend on the level of building envelope air tightness as well as user type. The results also show that there lies potential for improved comfort conditions when a zoned system is paired with a tight building, highly insulated envelope. Average whole house temperatures have remained very close in range between all houses during periods of cooling and non-cooling, however there is significant variation when temperatures are evaluated on a per floor level basis for Houses A, B, and Reno2050. The scope of this study has compared zone and central cooling systems to an extent that has not been shown in any of the literature reviewed, and this study has also provided validation for a longer study over an entire summer cooling season (summer 2013).

The major research project has set out to answer the following research questions:

1. What are the energy benefits of zone cooling compared to central air cooling systems?
2. What are the comfort benefits (i.e. temperature and relative humidity) across houses with zone cooling and central air cooling systems?

The questions were answered through the following approach:

(1) Field results have shown that the zoned system with a tight, highly insulated building envelope and particular user behaviour outperforms the central systems with a leaky envelope. The Reno2050 house consumes approximately 96% and 94% less for total cooling energy use than House A and House B respectively. The energy models show that an improved building envelope for air tightness and thermal resistance can decrease energy use by approxiamtely 60%.

(2) Field results from energy meters have shown a snapshot of 3 different houses – one with zoned and two with central systesms – for total cooling energy use. Equipment type for central systems

consume more energy than zoned cooled systems, and equipment age has shown to consume more energy for older equipment types.

(3) Level of use between systems types has a significant effect on energy use. User type has shown Houses A and B are considered heavy users of energy and Reno2050 house is a light user of energy. The zoned system from the Reno2050 is only used three times during the entire study duration, and Houses A and B usage levels vary during the study period. Fan energy use for House A and House B have been significant. There are periods where House B operates in a fan only mode, temperature readings across floor levels show that there is no improvement in temperature, and air stratification still occurs on upper floor levels.

(4) Four energy model cases were created to benchmark field measurements and facilitate the study comparison. When the energy models are compared to field results, the Reno2050 house consumes 60% less energy than its counterpart energy model Case 1, and Houses A and B consume approximately 50% more energy than its counterpart energy model Case 4. This comparison shows how the level of use has a significant effect on overall energy consumption.

(5) On temperature, for the Reno2050 House less energy is needed to maintain more equal temperatures compared with House A and House B and is mainly due to the high performance building envelope, since the Reno2050 House is in a period of non-cooling for the majority of the study period. A cooling period in July, also shows that when both Houses B and Reno2050 turn on at the same time, the zoned system at the Reno2050 house provides cooling to the 3rd floor at a faster rate than House B.

IN-HOME QUESTIONNAIRE

Dear Homeowner, the *Renovation 2050* program is in underway. The next steps for each Homeowner are to fill out this brief In Home Survey. By completing this survey, the aim is to document and compile relevant data of your home for pursuing the next steps towards this research project. Future work will involve planning for the Summer Season in 2013, which will include monitoring the actual power output of your homes air-conditioning unit.

NAME:____**DATE**: ___________________________

ADDRESS: ________________________

1. **How many people live in the home?** *# of ____ Adults # of ____ Children*
   How long have you lived at the house? *# of ____ years*
   Approximately how old is your home? *# of ____ years*

2. **Has the house been recently renovated? If yes, please provide a general description of the renovations and when they occurred:**
   ____

3. **Do you have a central air conditioner? If yes how old is it?** *# of ____ years*
   a. What is the make/model number:______________________________
   b. What is the SEER rating (if known):______________________________
   c. What is the rated capacity in kilowatts (kW) (if known): **______________**
   d. Are there any stand-alone window units? If yes, how many?: ____________
4. **What types of windows are in the home?** Double Pane Glass / Single Pane Glass
5. **What are the windows frames made up of?** Wood / Aluminum / Vinyl
6. **Have the windows ever been replaced? If yes, when?: ____________**
7. **Are there any areas in the home that are too hot?**
   a. **Describe where and when:_____________________________________**
8. **Has anyone ever experienced areas in the home that are regularly too drafty or too stuffy?**
   a. Describe where and when:_____________________________________
9. **Questions about your basement:**
   a. Is your basement cooled? Yes / No
   b. What is your basement typically used for (ex. Storage, living, sleeping etc.)
10. **Does the home have a programmable thermostat?** Yes / No
    If yes, what are the typical settings:

	Day		**Night**	
SUMMER	____AM to ____PM	______°C/F	____PM to ____AM	______°C/F

APPENDIX B: BLOWER DOOR TEST DATA

Specifications | Other Factors | Air Leakage Test Data

Test Conditions ○ CGSB ◉ As Operated

Test Type: 1 blower - whole hous

Outside Temperature: 20 °C

Barometric Pressure: 101.3 kPa

Results

Flow Co-efficient	109.27	Correlation Co-efficient	0.9996	ACH @ 50 Pa	7.18	Relative Error (%)	1.3
Flow Exponent	0.6512	Heated Volume	700	ELA @ 10 Pa	1964.87	Update	

Test 1/Equip1

Fan Type: Retrotec 2000/3000

Manometer: Ryerson's

Initial Static Pressure: 0 Pa

Final Static Pressure: 0 Pa

Inside Temperature: 18 °C

Zone Heated Vol: 700 m³

Hse Pressure Pa	Fan Pressure Pa	Measured Flow L/s	Flow Ranges	Measured Flow L/s	Corrected Pressure Pa	Corrected Flow L/s	Error %
-0	13.2	0	Open	939	0.0	942	0.0
-30	17.1	0	Open	1002	30.0	1006	-0.5
-35	20.3	0	Open	1097	35.0	1100	0.5
-40	24.1	0	Open	1201	40.0	1206	0.1
-45	28	0	Open	1301	45.0	1305	-0.2
-50	32	0	Open	1396	50.0	1401	-0.3
-55	35.4	0	Open	1471	55.0	1476	0.6
-60	40.1	0	Open	1571	60.0	1577	-0.3
0	0	0	Open	0	0.0	0	0.0
0	0	0	Open	0	0.0	0	0.0
0	0	0	Open	0	0.0	0	0.0
0	0	0	Open	0	0.0	0	0.0
0	0	0	Open	0	0.0	0	0.0
0	0	0	Open	0	0.0	0	0.0
0	0	0	Open	0	0.0	0	0.0
0	0	0	Open	0	0.0	0	0.0

Figure D2: House B Blower Door Test Results

Specifications | Other Factors | Air Leakage Test Data

Test Conditions ○ CGSB ◉ As Operated Test Type: 1 blower - whole hous

Outside Temperature: 20 °C

Barometric Pressure: 101.3 kPa

Results

Flow Co-efficient	157.54	Correlation Co-efficient	0.9998	ACH @ 50 Pa	10.56	Relative Error (%)	1.0
Flow Exponent	0.6563	Heated Volume	700	ELA @ 10 Pa	2866.19	Update	

Test 1/Equip1

Fan Type: Retrotec 2000/3000 Manometer: Ryerson's

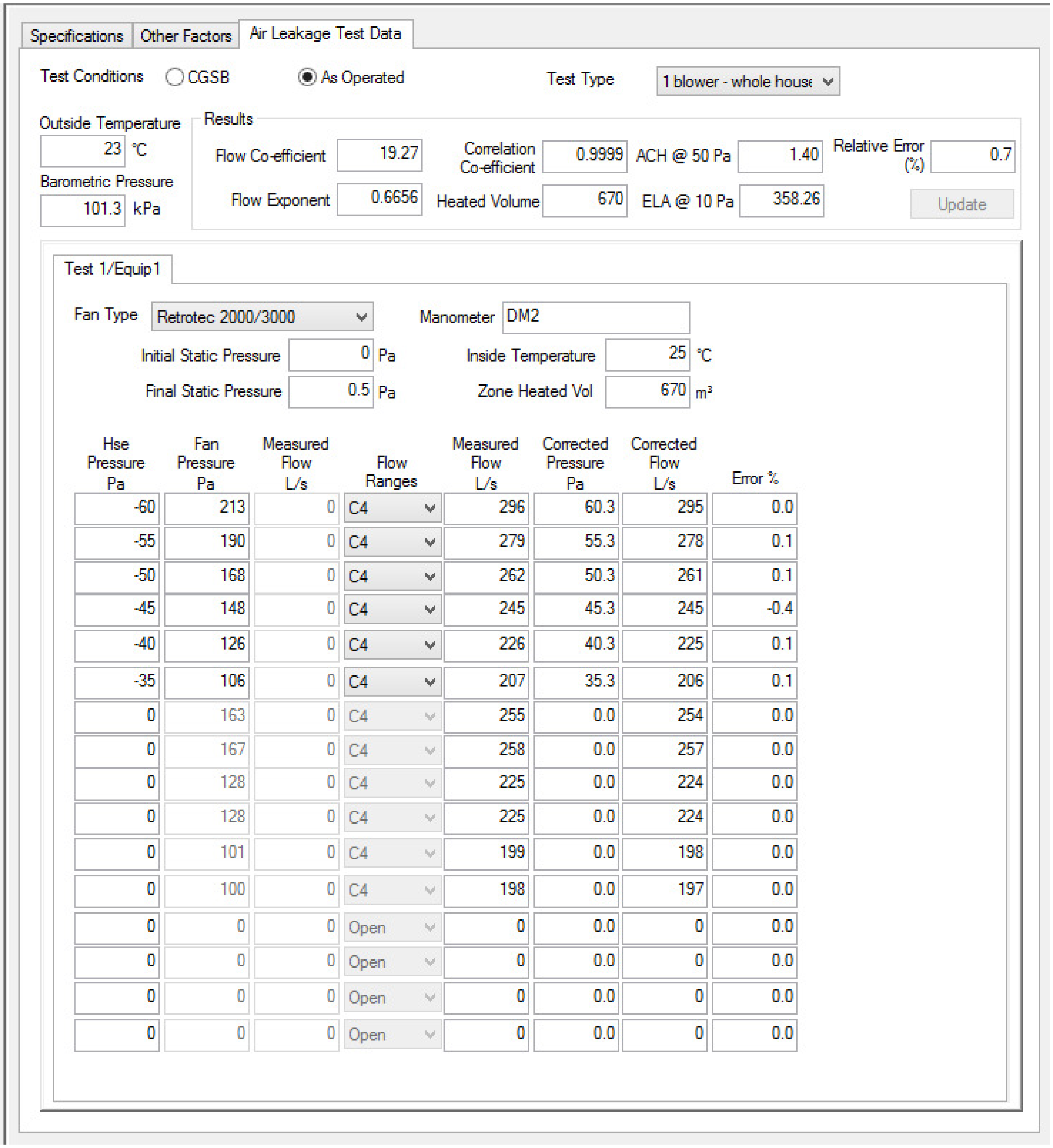
Initial Static Pressure: 0 Pa Inside Temperature: 18 °C

Final Static Pressure: 0 Pa Zone Heated Vol: 700 m³

Hse Pressure Pa	Fan Pressure Pa	Measured Flow L/s	Flow Ranges	Measured Flow L/s	Corrected Pressure Pa	Corrected Flow L/s	Error %
-0	27.9	0	Open	1382	0.0	1387	0.0
-30	33.6	0	Open	1470	30.0	1475	-0.5
-35.1	40.2	0	Open	1613	35.1	1618	0.6
-40	47.7	0	Open	1763	40.0	1769	0.3
-45	55.8	0	Open	1911	45.0	1918	-0.1
-50	63.9	0	Open	2049	50.0	2056	-0.2
-55	72.4	0	Open	2185	55.0	2192	-0.3
-60	80.1	0	Open	2300	60.0	2307	0.3
0	0	0	Open	0	0.0	0	0.0
0	0	0	Open	0	0.0	0	0.0
0	0	0	Open	0	0.0	0	0.0
0	0	0	Open	0	0.0	0	0.0
0	0	0	Open	0	0.0	0	0.0
0	0	0	Open	0	0.0	0	0.0
0	0	0	Open	0	0.0	0	0.0
0	0	0	Open	0	0.0	0	0.0

APPENDIX B: BLOWER DOOR TEST DATA

Figure D3: House C Blower Door Test Results



Specifications | Other Factors | Air Leakage Test Data

Test Conditions: ○ CGSB ◉ As Operated

Test Type: 1 blower - whole house

Outside Temperature: 23 °C

Barometric Pressure: 101.3 kPa

Results

Flow Co-efficient: 19.27

Flow Exponent: 0.6656

Correlation Co-efficient: 0.9999

Heated Volume: 670

ACH @ 50 Pa: 1.40

ELA @ 10 Pa: 358.26

Relative Error (%): 0.7

Update

Test 1/Equip1

Fan Type: Retrotec 2000/3000

Manometer: DM2

Initial Static Pressure: 0 Pa

Final Static Pressure: 0.5 Pa

Inside Temperature: 25 °C

Zone Heated Vol: 670 m³

Hse Pressure Pa	Fan Pressure Pa	Measured Flow L/s	Flow Ranges	Measured Flow L/s	Corrected Pressure Pa	Corrected Flow L/s	Error %
-60	213	0	C4	296	60.3	295	0.0
-55	190	0	C4	279	55.3	278	0.1
-50	168	0	C4	262	50.3	261	0.1
-45	148	0	C4	245	45.3	245	-0.4
-40	126	0	C4	226	40.3	225	0.1
-35	106	0	C4	207	35.3	206	0.1
0	163	0	C4	255	0.0	254	0.0
0	167	0	C4	258	0.0	257	0.0
0	128	0	C4	225	0.0	224	0.0
0	128	0	C4	225	0.0	224	0.0
0	101	0	C4	199	0.0	198	0.0
0	100	0	C4	198	0.0	197	0.0
0	0	0	Open	0	0.0	0	0.0
0	0	0	Open	0	0.0	0	0.0
0	0	0	Open	0	0.0	0	0.0
0	0	0	Open	0	0.0	0	0.0

APPENDIX C: Summary of Energy Bills

Table C1: Total Gas Consumption (m3)

Month	House A	House B	RENO2050 House
Jan-12	0	776	245
Feb-12	0	466	170
Mar-12	452	418	138
Apr-12	392	253	116
May-12	0	182	90
Jun-12	65	71	37
Jul-12	63	59	39
Aug-12	36	34	0
Sep-12	110	97	53
Oct-12	175	199	58
Nov-12	423	384	126
Dec-12	435	398	128
Jan-13	793	771	236
Feb-13	810	796	220
Mar-13	620	489	175
Apr-13	567	546	169
May-13	196	162	73
Jun-13	109	82	44
Jul-13	55	0	40
Aug-13	59	51	48
Sep-13	122	114	58
Oct-13	114	111	0
Nov-13	426	389	0
Dec-13	0	620	0
Total	**6022**	**7468**	**2263**

Table C2: Total Electricity Consumption (kWh)

Date	House A	House B	RENO2050
Jan-12	2013	3381	1246
Mar-12	1882	2174	1177
May-12	3336	1324	1009
Jul-12	3583	1881	876
Sep-12	2162	1843	1258
Nov-12	2349	3530	1424
Jan-13	1856	3754	1300
Mar-13	1821	2709	1217
May-13	2612	1258	907
Jul-13	3225	1455	794
Sep-13	1862	0	0
Nov-13	0	0	0
Total	**5837**	**2713**	**1701**

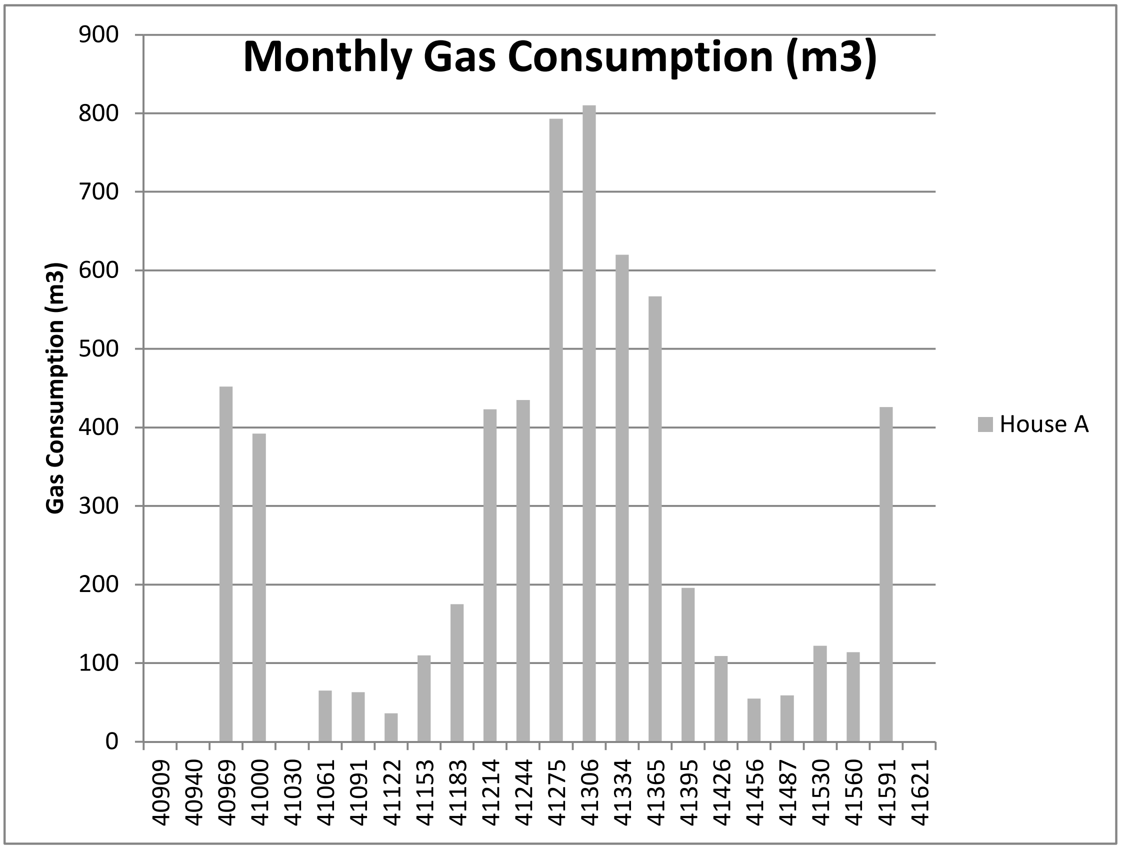


Figure C1: House A Monthly Gas Consumption

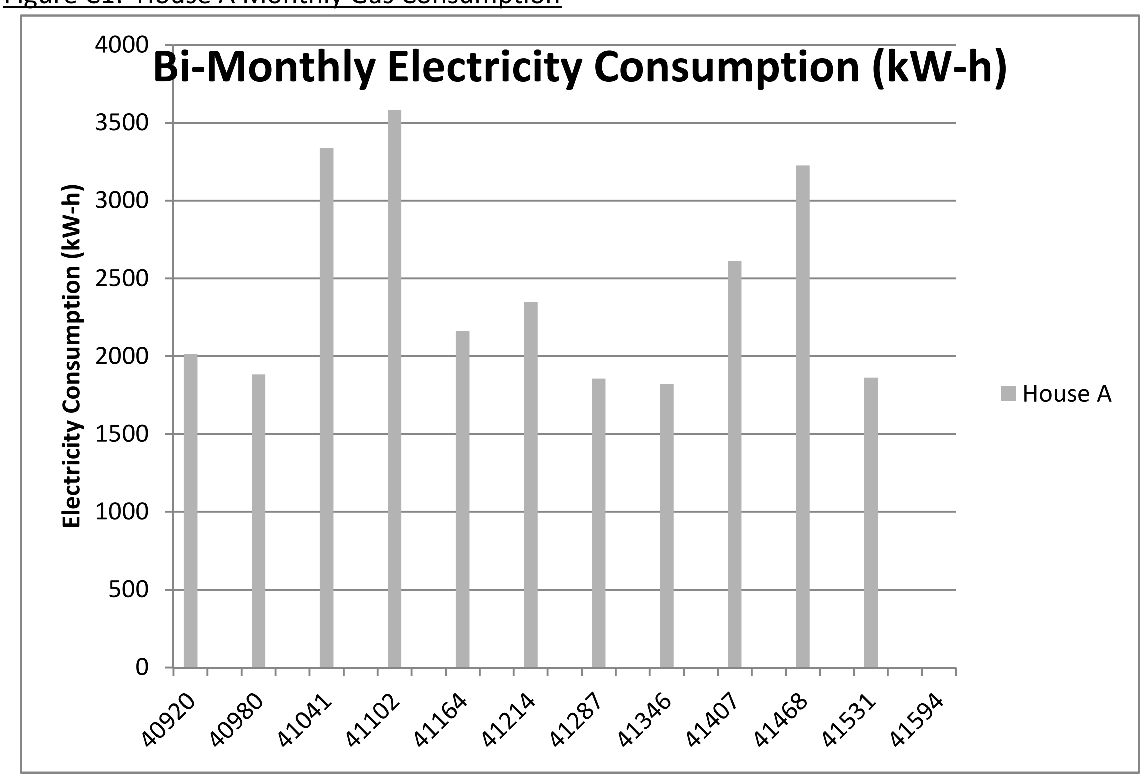


Figure C2: House A Bi-Monthly Electricity àConsumption

APPENDIX C: Summary of Energy Bills

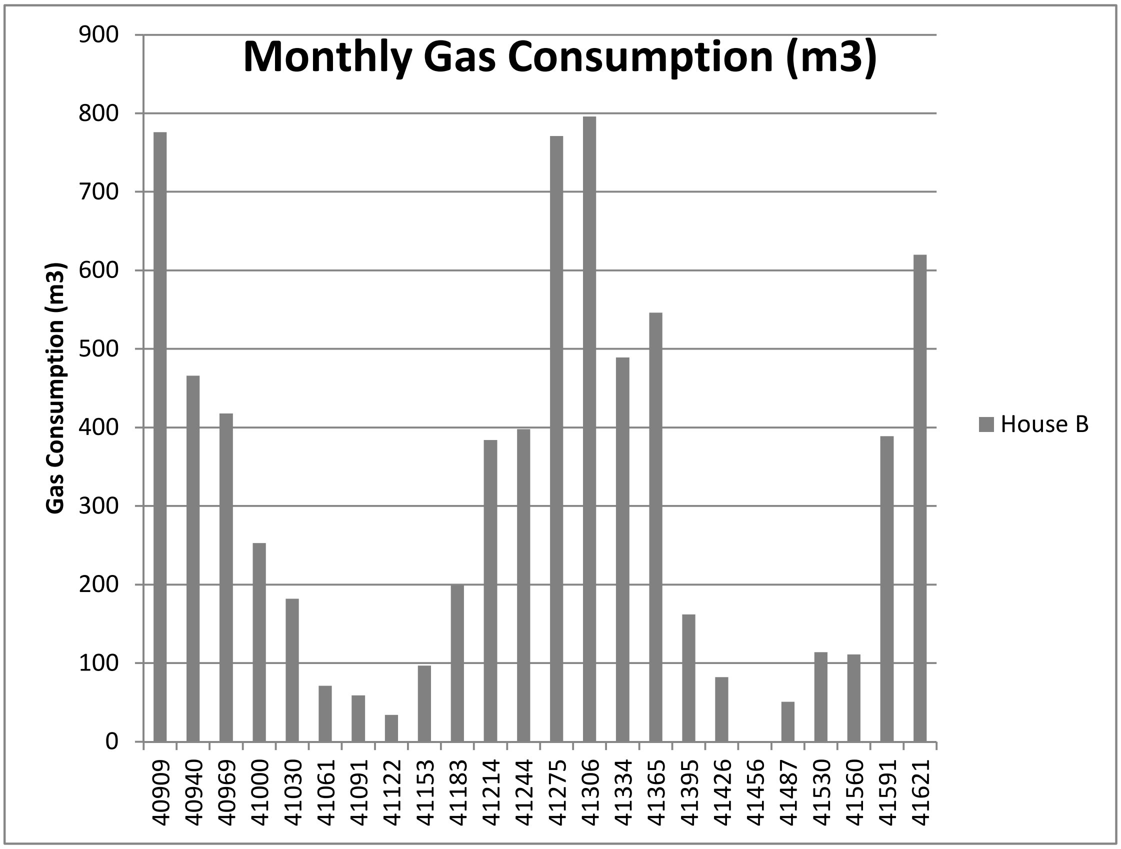


Figure C3: HouseB Monthly Gas Consumption

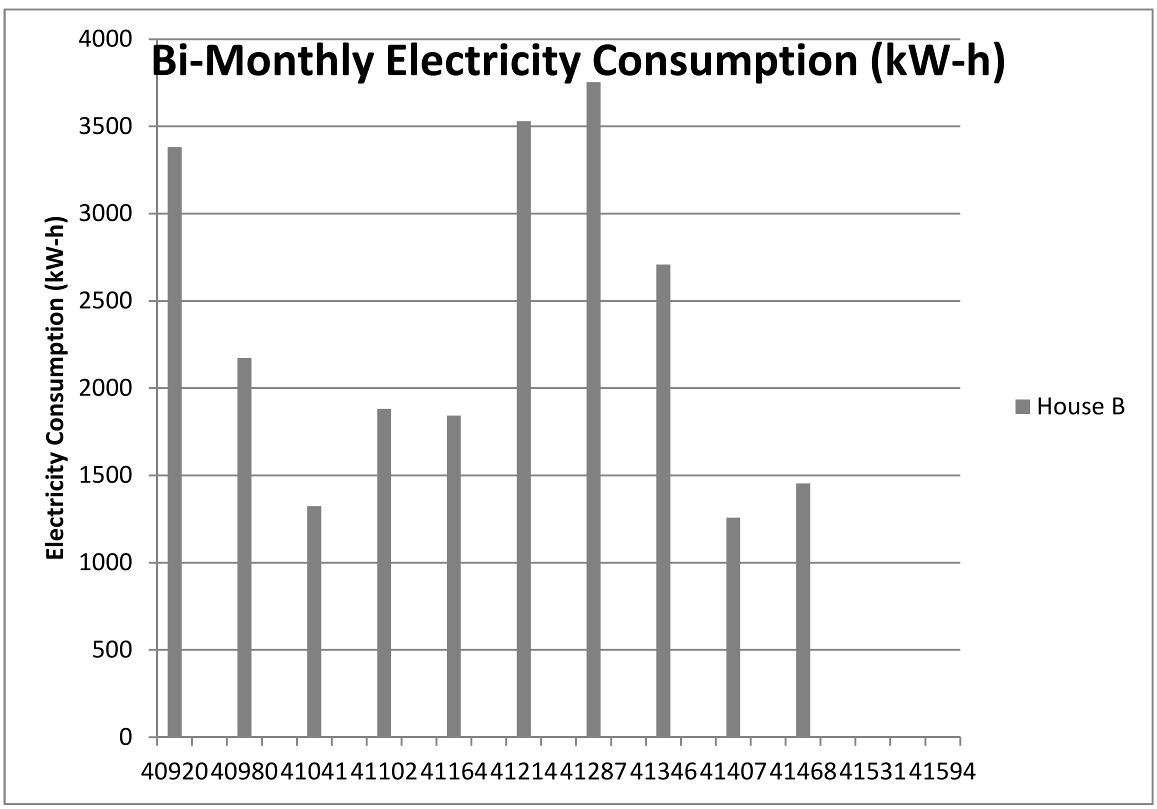


Figure C4: House B Bi-Monthly Electricity àConsumption

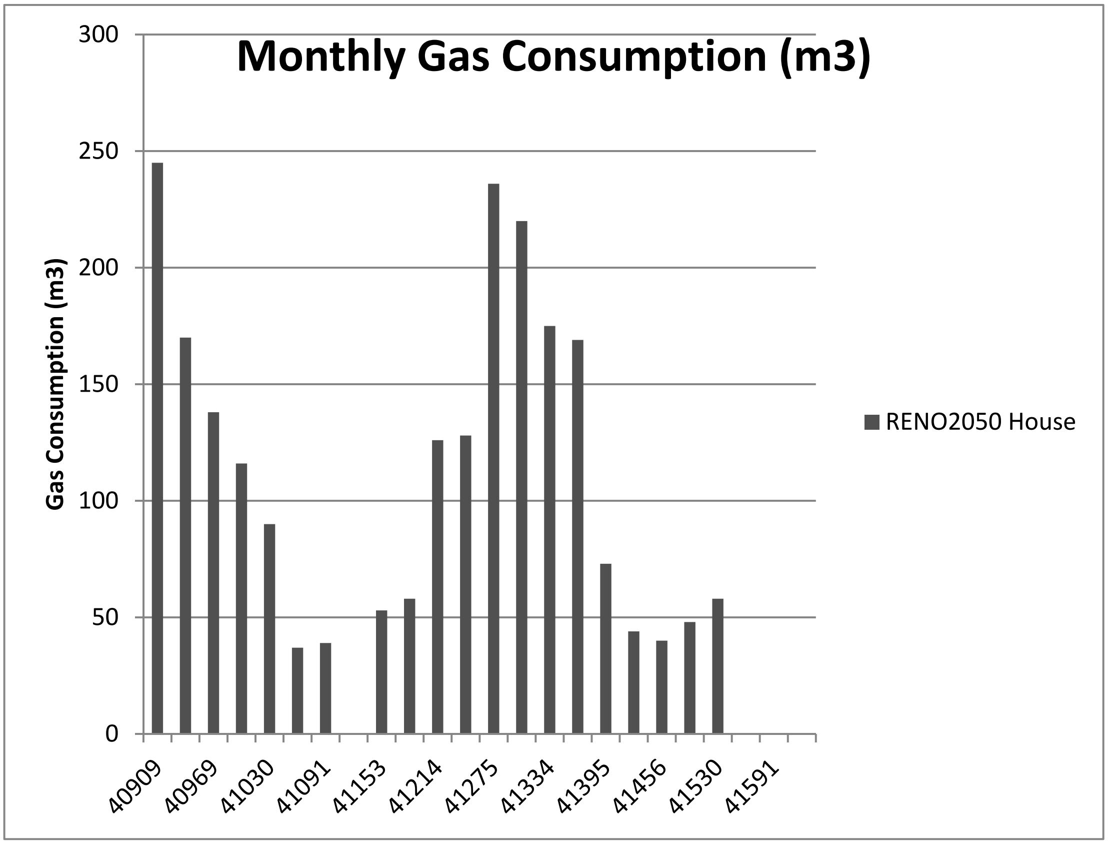


Figure C5: RENO2050 House Monthly Gas Consumption

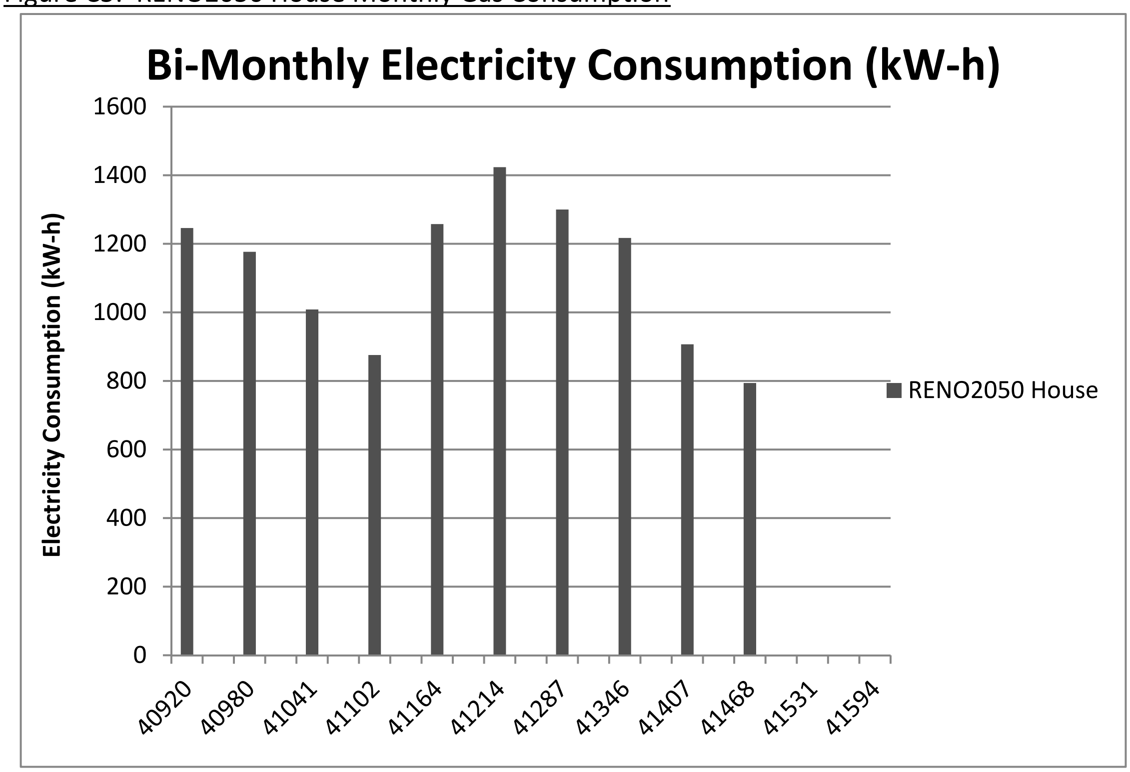
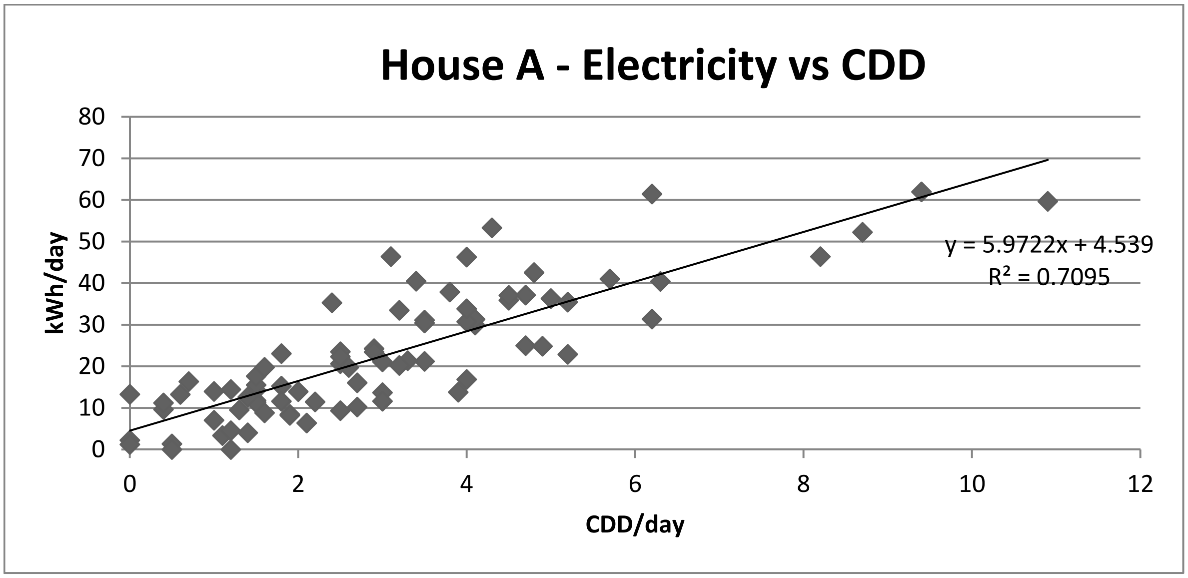
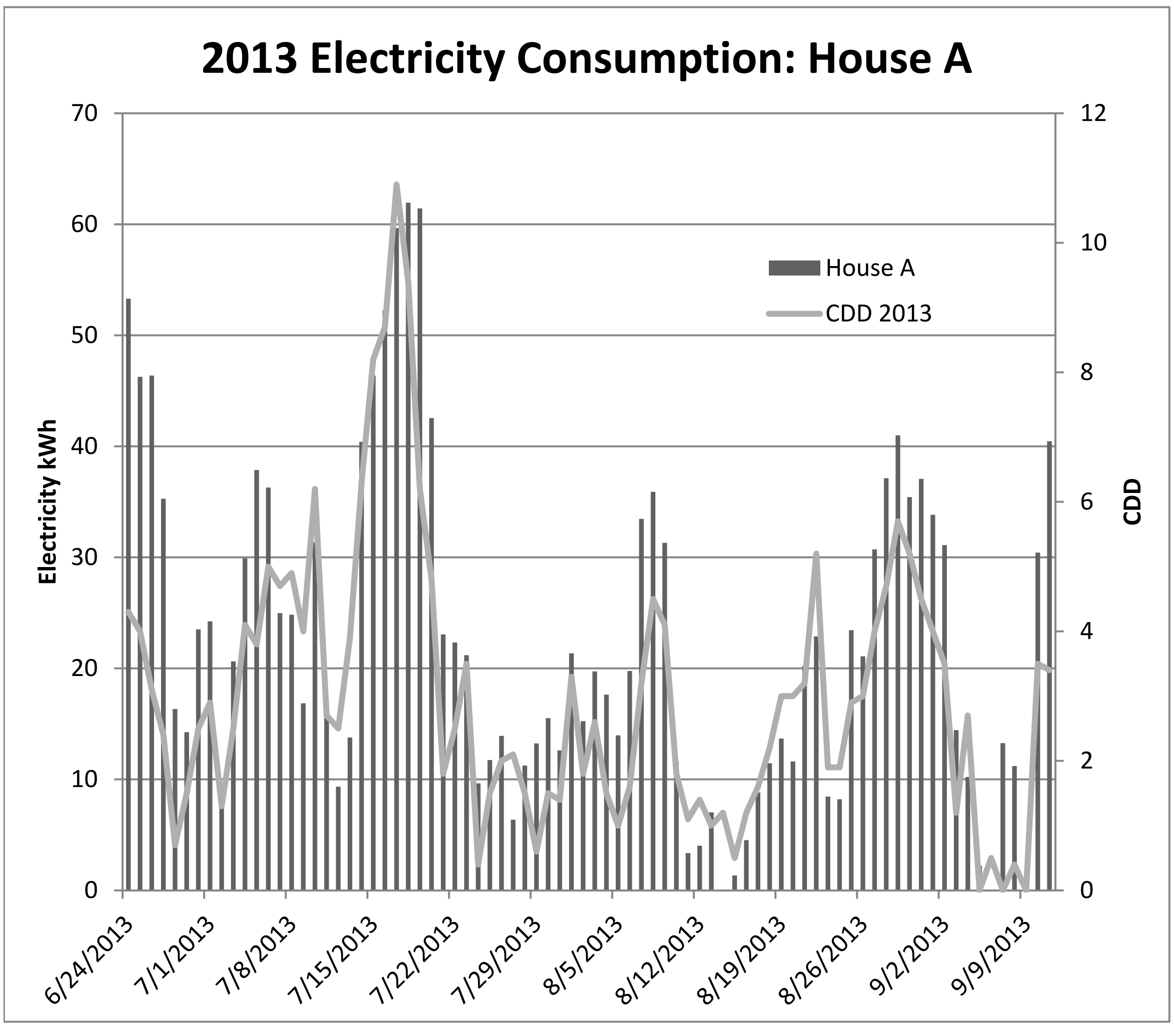
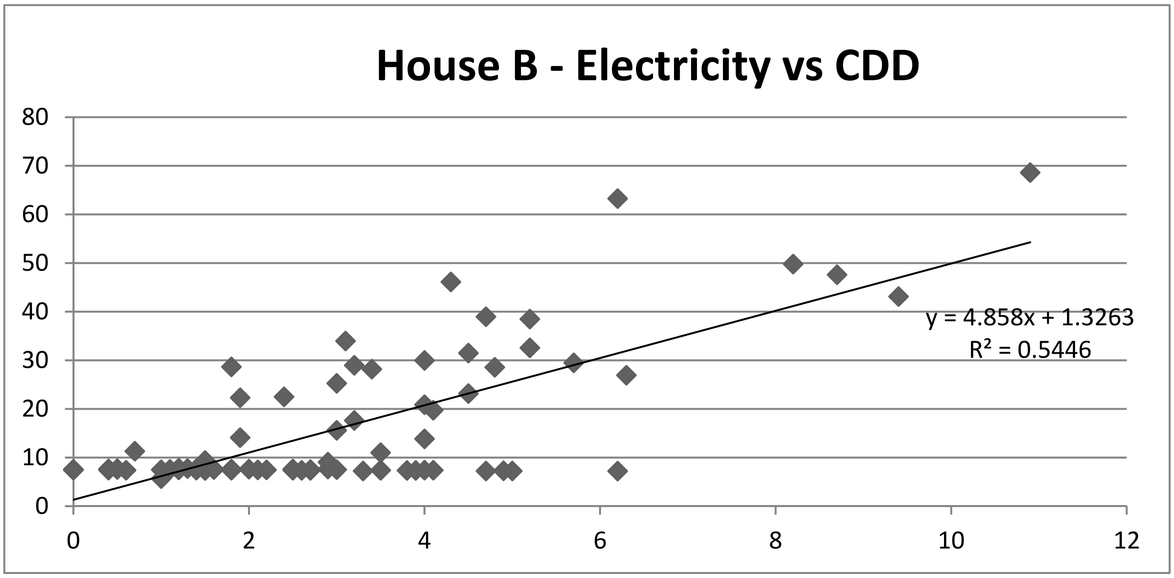
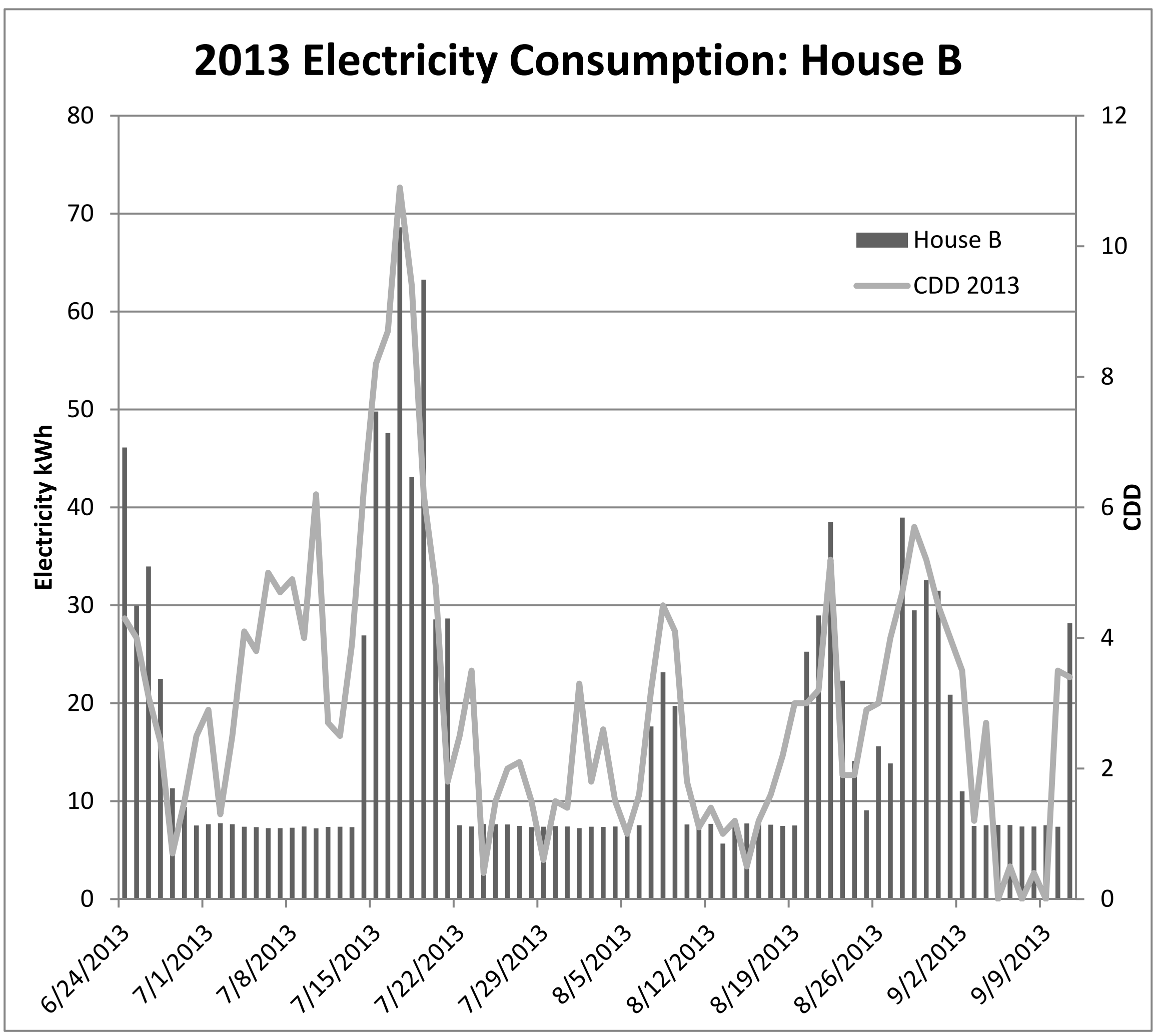


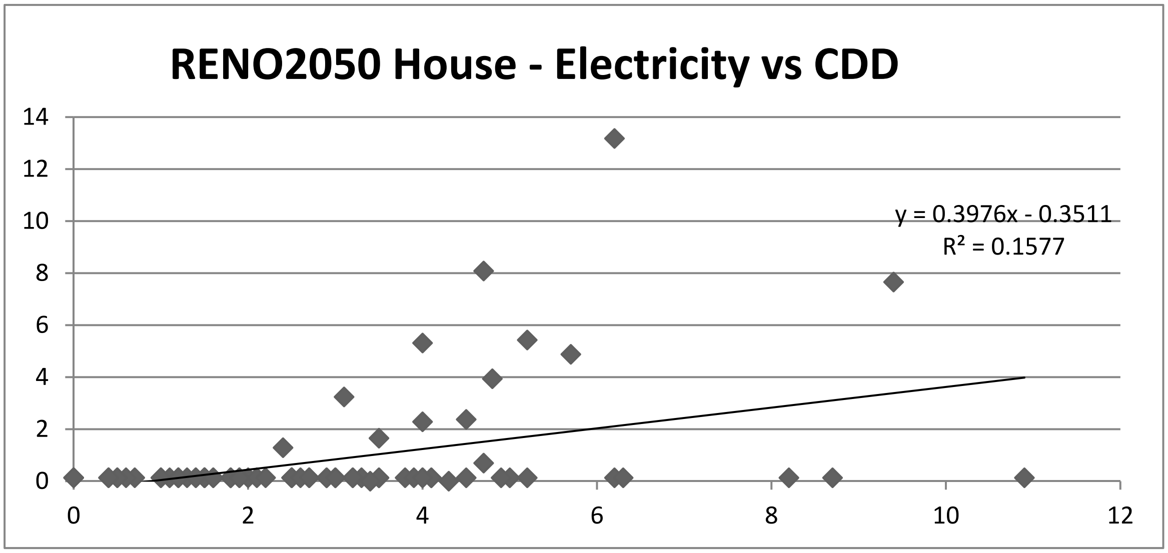
Figure C6: RENO2050 House Bi-Monthly Electricity àConsumption

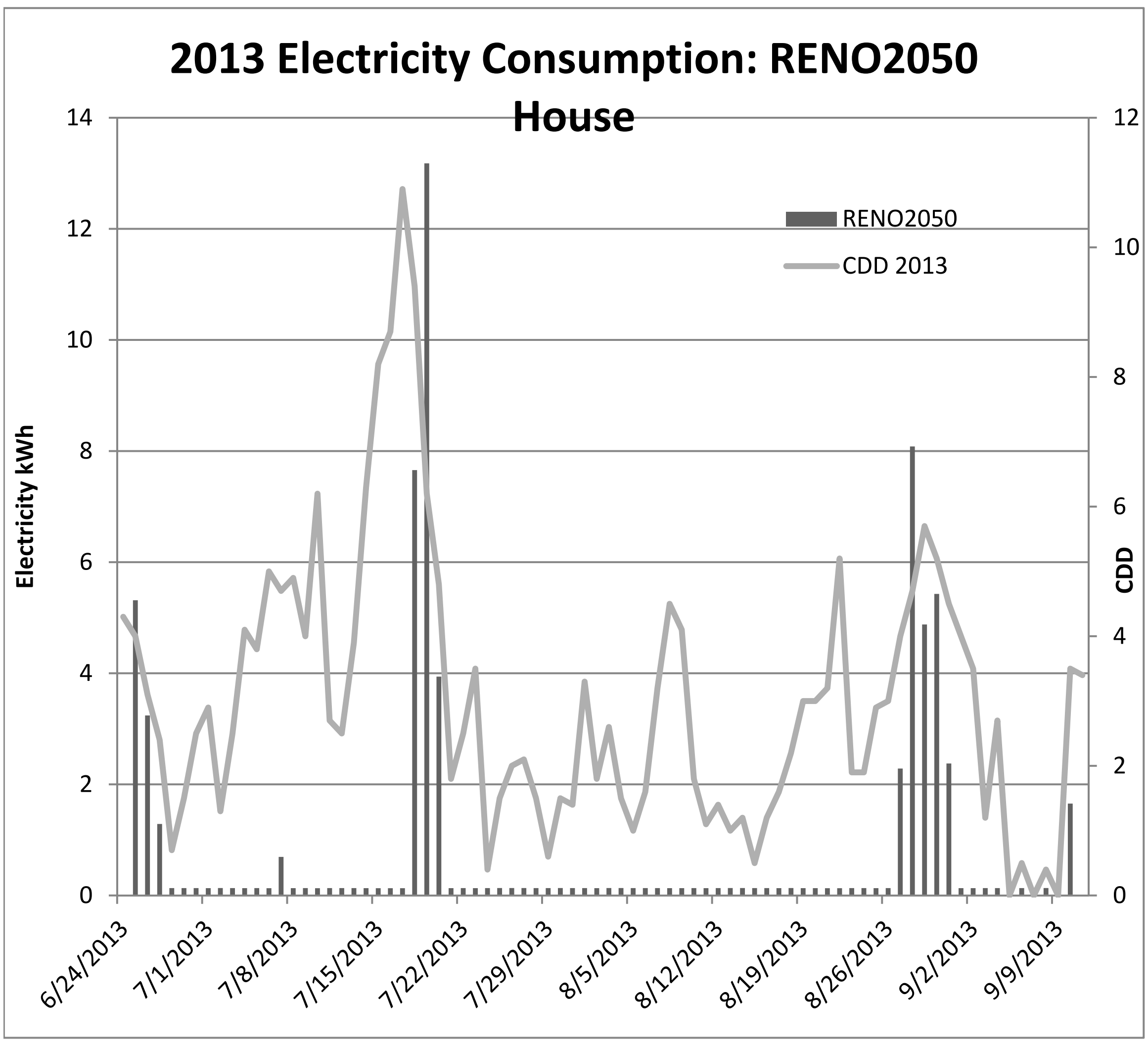

House A - Electricity vs CDD
kWh/day
CDD/day
y = 5.9722x + 4.539
R² = 0.7095
0
10
20
30
40
50
60
70
80
0
2
4
6
8
10
12


2013 Electricity Consumption: House A
Electricity kWh
CDD
House A
CDD 2013
0
10
20
30
40
50
60
70
0
2
4
6
8
10
12
6/24/2013
7/1/2013
7/8/2013
7/15/2013
7/22/2013
7/29/2013
8/5/2013
8/12/2013
8/19/2013
8/26/2013
9/2/2013
9/9/2013


House B - Electricity vs CDD
80
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
y = 4.858x + 1.3263
R² = 0.5446


2013 Electricity Consumption: House B
Electricity kWh
CDD
House B
CDD 2013
80
70
60
50
40
30
20
10
0
12
10
8
6
4
2
0
6/24/2013
7/1/2013
7/8/2013
7/15/2013
7/22/2013
7/29/2013
8/5/2013
8/12/2013
8/19/2013
8/26/2013
9/2/2013
9/9/2013


RENO2050 House - Electricity vs CDD
y = 0.3976x - 0.3511
R² = 0.1577
14
12
10
8
6
4
2
0
0
2
4
6
8
10
12


2013 Electricity Consumption: RENO2050 House
RENO2050
CDD 2013
Electricity kWh
CDD
14
12
10
8
6
4
2
0
12
10
8
6
4
2
0
6/24/2013
7/1/2013
7/8/2013
7/15/2013
7/22/2013
7/29/2013
8/5/2013
8/12/2013
8/19/2013
8/26/2013
9/2/2013
9/9/2013

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