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SMART POWER FOR SMART HOME

Inverter Controls, Power Factor Corrections, and Peak Demand Reductions

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PREFACE

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ABSTRACT

Typical American households have a dynamic power quality factor varying from 0.8 to 0.95 depending on the signature of loads and their use at the time. (Appliances such as HVAC, motors, and lighting generate reactive and harmonic power, which is typically about 20% of the power consumption.) While photovoltaic (PV) panels via inverter provides mostly real power to home loads, the reactive power consumed by the loads would need to come from the electric grid and thus lowering the energy efficiency of the total system. Surging demand on reactive power at peak hours further induces instability to the grid. In this study, three aspects of this challenges and solutions are investigated, active power filter (APF) design, load disaggregation system design, energy modeling and testing of the systems above.

We propose a grid tied inverter (GTI) integrated with APF that harnesses power from the renewables and cancels the reactive Q and harmonics H in the meantime. The power flow to or from the grid is thus purely sinusoidal and active. The proposed concept can be realized by using the one-cycle control (OCC) technology, featuring fast and stable dynamics and precise harmonic and reactive cancellation. Another long term solution we proposed is to promote behavioral adaptive changes via load disaggregation. This starts with a deep understanding of energy related human behaviors. The proposed power monitoring system will measure the performance of the APF/inverter, report the overall load, and recognize the consumer usage patterns. The systems have been fully implemented, tested and demonstrated for effectiveness during the in house testing at a "smart home" location**.** The evaluation was conducted in a 'smart home' to explore how a variety of options for mechanical equipment efficiency and building construction practices affect the net-load profile for ZNE homes. Several different operating scenarios were tested with combinations of various types of loads in the home, and across a range of power draw from 100 Watts to 1.75 kW. The research team conducted a parametric analysis of several different measures to characterize their impact on load profile for the home in every day of the year. The parameters that were found to have the biggest impact on the load profile were the energy source (gas or electric) of equipment and appliances, the level of onsite solar generation and the capacity and operation strategy of onsite electric storage. The simulation results show that by simply setting a fixed limit to the charge and discharge rate, the onsite electric storage was extremely effective in smoothing out the load profile. With this information, we can further study and discover means to save energy either by providing guidance to the users or implement control systems to help users save energy seamlessly.

Keywords: APFC, Power factor correction, One-cycle control, Load Disaggregation, Algorithm, Load Signature Analysis.

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TABLE OF CONTENTS

PREFACE ..... **i**

ABSTRACT ..... **ii**

TABLE OF CONTENTS ..... **iii**

LIST OF FIGURES ..... **iv**

EXECUTIVE SUMMARY ..... Error! Bookmark not defined.

CHAPTER 1: Implementation of OCC-APF for smart home **4**

CHAPTER 2 FIELD EVALUATION OF ACTIVE POWER FILTER **9**

2.1 Project Background 9

2.1.1 Objectives 9

2.2 Methodology and Technical Approach 10

2.3 Results and Discussion 11

2.3.1 Baseline Characteristics 11

2.3.2 Impacts of APFC: 12

2.3.3 Synthesis 15

2.4 Conclusions 16

CHAPTER 3: Load Signature Analysis and Wireless Monitoring System **17**

3.1 Electrical Characteristics Capture 17

3.1.1 Methodologies 17

3.1.2 Hardware design 17

3.1.3 Firmware Design 19

3.2: Disaggregation 22

3.2.1 Backward learning 22

3.3: Communications 24

3.3.1 PCB to Gateway Communication Protocol 24

3.3.2 Gateway to Server Communication Protocol 24

3.4: User Interface and Usage Modes 25

3.4.1 Normal Operational mode 25

3.4.2 Training mode 26
3.5: Industrial Design 28
CHAPTER 4 INTEGRATED DESIGN AND CONTROL OF HVAC, GENERATION, AND STORAGE FOR MANAGEMENT OF LOAD PROFILES IN ZNE HOMES 31
4.1 Project Background 31
4.2 Objectives 32
4.3 Methodology and Technical Approach 33
4.4 Simulation Parameters 34
4.5 Results and Discussion 45
4.6 Conclusions 56
GLOSSARY 58
Works Cited 60

LIST OF FIGURES

Figure 1 One line diagram of the APF connection circuit 5
Figure 2 OCC-APF circuit diagram 6
Figure 3 Printed circuit board for OCC-APF 6
Figure 4 The OCC-APF Prototype, Left-Front view, Right-rear view 7
Figure 5 Schematic for main electrical panel and APFC connection 11
Figure 6 Example load profile from test home 12
Figure 7 15-second increment data for "Vacuum & Air Compressor" test with and without the active power filter 13
Figure 8 Summary results for APFC tests in eight different modes of operation 14
Figure 9 Modularized PCB design diagram 17
Figure 10 PCB Schematics 18
Figure 11 PCB Layout 19
Figure 12 Implemented System Level Firmware Flowchart for ARM Processor on PCB 20
Figure 13 KNN algorithm diagram two dimensional projection representation 22
Figure 14 Data package definition between PCB and Gateway 24
Figure 15 Gateway to Server Communication data package definition 24
Figure 16 User Interface for Load Monitoring System (Home) 26
Figure 17 Training Mode User Interface 27
Figure 18 Enclosure Interior 28
Figure 19 Enclosure with lid on 29
Figure 20 Finished Product pictures 30
Figure 21 Rendering of the single family building modeled 33
Figure 22 California Climate Zones 35

Figure 23 Annual electric end uses for a mixed energy single family building (RASS) 38
Figure 24 Annual gas end uses for a mixed energy single family building (RASS) 38
Figure 25 – Annual electric end uses for an all-electric single family building (RASS) 39
Figure 26 – Daily electric load profiles for non-HVAC equipment and appliances 40
Figure 27 Daily gas load profiles for non-HVAC equipment and appliances Figure 28 – Daily load profile from non-HVAC equipment and appliances 41
Figure 29 Normalized residential hot water use published in the REMP by the Commonwealth of Australia 43
Figure 30 – Resulting daily hot water use profile 44
Figure 31 - The range of different model scenarios considered 45
Figure 32 – The all-electric ZNE home in each of California's climate zones 46
Figure 33 – Net load profile for 2013-T24 compliant home in CA CZ 12 with different levels of onsite solar electricity generation 47
Figure 34 – Low level improvements to a ZNE home 48
Figure 35 – Mid level improvements to a ZNE home 49
Figure 36 - High level improvements to a ZNE home. 50
Figure 37 – Electric load due to heating and cooling 51
Figure 38 – Electric load due to water heating 52
Figure 39 - Stacked load profile of the all-electric home with each level of efficiency improvements - winter 53
Figure 40 - Stacked load profile of the all-electric home with each level of efficiency improvement - summer 54
Figure 41 Limited electric storage charge and discharge rates 55

EXECUTIVE SUMMARY

Introduction

To better understand the demand response is to gain more knowledge directly from the end user. Where the energy is drawn from the grid will provide extremely useful information once we understand how people are interacting with devices at home. Several factors should be taken into consideration in order to find patterns in that pool of information gathered. Differentiating the usage of the various loads while drawing cleaner power via an active power filter, benefits can be identified to end users and the grid's stability while producing better understanding in possibly effectively increasing energy efficient. Furthermore, conducting a test demonstration as well as establishing a model simulation, clearer results revealed that allowing an active power filter system and promoting load disaggregation could lead to positive impact on possible energy efficiency overall.

Load signatures of devices can be altered by using an active power filter system, which corrects the power factor to near unity. During this period, a 1.5 kVA one-cycle controlled active power filter was prototyped. The demonstration of such a system showed that the power factor was corrected to >0.98 for all type of the loads in the house including Lights, Lights & Electronics, Electronics, Vehicle Charging, Kitchen Appliances, Vacuum & Air Compressor, Whole House Fan, Water Heater & Vacuum, Washer & Dryer. In addition, subsequent modeling and simulations were conducted to assist in developing further understand of loads as well as consumer behaviors and usage patterns to ultimately produce measures via incentives and/or regulations to achieve energy savings and efficiency.

Project Purpose

For the benefit consumers and utilities, load signature disaggregation and APF prototype devices were developed to restore the sine wave of at a household level and to capture load signatures of multiple devices which could be extend to monitor the entire the house to monitor, record, and disaggregate power consumption of devices. In addition, to simplify and encourage optimal usage of the device, the prototype will also provide an easy to understand viewing feature by directly displaying users' devices energy consumption information at their fingertips. Meanwhile, data gathered could provide utilities a better understanding of consumer energy consumption and to promote energy savings and efficiency. A simulation model is developed at the same time with different profiles. A test of the prototype devices is conducted at a smart home.

Project Results

- Developed and tested APF device with OCC technology.
- Developed PCB and algorithms to capture and disaggregate plug load devices.
- Defined server end protocol to establish a communicational channel between PCB and a mobile friendly interface.

- Implement and test demonstration site of the device for efficacy.
- Establish modeling and simulation scenarios to capture the varying consumption levels of energy and taking into consideration the unpredictability of behaviors to produce a better understanding of integration of device and behavior in optimal energy savings and efficiency.

Project Benefits

Technological advancements are produced in algorithmic approaches in load disaggregation. Simplifications on measuring devices are made to be more compatible at household levels. Modeling and simulations lend to a more precise identification and consideration of the integrating device and behavior consumption to reveal energy needs. For the utilities and stakeholders, what are the best solutions that will lead to better energy management should be explored as it will be vital to the future of energy management. This project has examined available technological advances to integrate with consumption behavior in providing a better understanding of which energy efficient improvements could be deployed for energy savings. Incentivizing energy monitoring and managing are a beginning to such a future that not only effects energy consumption and grid stability but ultimately to a more efficient environment.

The next potential applications include:

- Implement APF with solar panel inverters (and batteries if available, for the best results), to achieve near zero reactive power draw while consuming zero energy from the grid generation.
- Dynamically upscale APF to be multi-house level power factor correction. By doing this, the static power consumption of APF is reduced to one of N houses. If this were to be taken to the next step, the utilities has the opportunity to implement the APF with a solar panel before distributing the electricity to each house, to even further reduce the burden on the grid.

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CHAPTER 1:
Implementation of OCC-APF for smart home

For a typical American household, the power quality factor varying from 0.8 to 0.95 is observed depending on the loads and their use at the time. While PV via inverter provides mostly real power to home loads, the reactive power consumed by the loads would need to come from electric grid and thus lower the energy efficiency of the total system and reduce the system power delivery capability. Surging demand on reactive power at peak hours further induce instability to the grid. In this project period, we focused on implementing a one-cycle controlled active power filter (APF) for home that can dynamically adjust the power quality factor of the electric circuit of the home to near unity.

Household appliances such as HVAC, motors, and lighting generate reactive and harmonic power, which is typically about 20% of the power consumption. Conventional inverters do not absorb it, thus, the reactive and harmonic will flow to the power grid. In the extreme case when zero power is flowing between the grid and the home, the reactive and harmonic draw counts 100%, which causes power losses in the line, disturbance to the system, distortion to the voltage, and possible system instability.

Article (Smedley, Zhou and Qiao, Unified constant-frequency integration control of single phase active power filter 2001) introduced a simple, fast and precise control solution based on one-cycle control (Smedley and Cuk, One-cycle control of switching converter 1991) for a single-phase APF, with excellent harmonic and reactive cancellation result. In 2006, a GTI/APF was proposed in (G. Smedley n.d.) that demonstrated active power processing with reactive and harmonic cancellation capability for three-phase systems. This technology is adopted for the home power application in this project.

The one line diagram of the APF is shown in Figure 1, where i_s is the grid current, i_{load} is the combined home appliance and PV inverter current, while i_{APF} is the APF current.

$$i_s = i_{APF} + i_{load}$$

Without APF, we have

$$P_s + Q_s = P_{load} + Q_{load}$$

When the load reactive current is high, the power grid will suffer from more loss, more congestion, and instability.

With APF, we have

$$P_s + Q_s = P_{APF} + Q_{APF} + P_{load} + Q_{load}$$

Where P_s is the grid power, Q_s is the grid reactive power, P_{APF} is the power consumed by the APF, Q_{APF} is the reactive power generated by the APF to cancel the load reactive power, P_{load} is the load power, and Q_{load} is the load reactive power.

The function of APF is to eliminate the reactive current of the home, i.e.

$Q_{APF} = - Q_{load}$

As the result, we achieve:

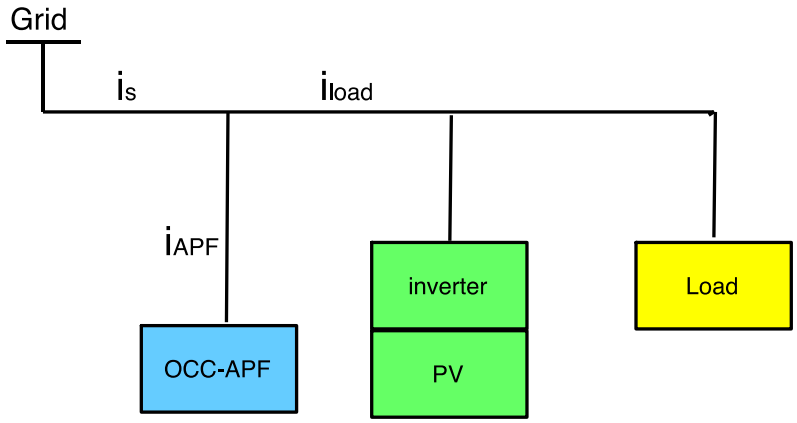
$P_s = P_{APF} + P_{load}$

$Q_s = Q_{APF} + Q_{load} = 0$

If we define the system efficiency as $\eta = \frac{P_{load}}{P_s}$, it is expected that the efficiency is at its maximum at full load, while the efficiency will drop at light load. In the extreme case at NZE condition, P_{load} will zero. Without APF, the reactive power Q_{load} from the load will flow back to the grid, which is very undesirable. This phenomenon has been a real concern for utility companies, because they will need to generate reactive current and delivery it to customers while the customers are not buying the power.

In order to promote renewable power generation and ZNE, it is necessary to eliminate the reactive power flow to the grid. The OCC-APF is an effective solution for that.

Figure 1 One line diagram of the APF connection circuit



The circuit diagram of the proposed grid tied APF inverter is shown in Figure 2. An H-bridge inverter is used as the power processing stage. The OCC control core shown in the dashed box controls the H-bridge to perform reactive and harmonic cancellation. The OCC control core is comprised of a clock, an integrator with reset, a comparator, a flip, flop, and a compensator, AV(s), as well as protection circuit. When the home pulls harmonic current as shown in Figure 3 as i_{load}, the OCC-APF will produce and reactive/harmonic current that cancels the one in the load and ensures the current draw from the grid, i_s, is pure sinusoidal and PF~0.99. The OCC method is simple, fast, and precise, yielding a cost effective, reliable, and versatile solution. Due to limited funding available in this phase, we built a 1.5kVA APF inverter to demonstrate the concept with a smart home. It can be used standalone or be placed next to a PV inverter for retrofit.

A printed circuit board layout was developed as shown in Figure 3 to connect the circuit components. Mechanical enclosure and thermal management system were designed and built. The final prototype is shown in Figure 4 for the front and rear view of the prototype. The front panel features circuit breaker, LED light status indicator, and air vent. The rear panel shows current sensor, power connectors, and fan guards.

Figure 2 OCC-APF circuit diagram

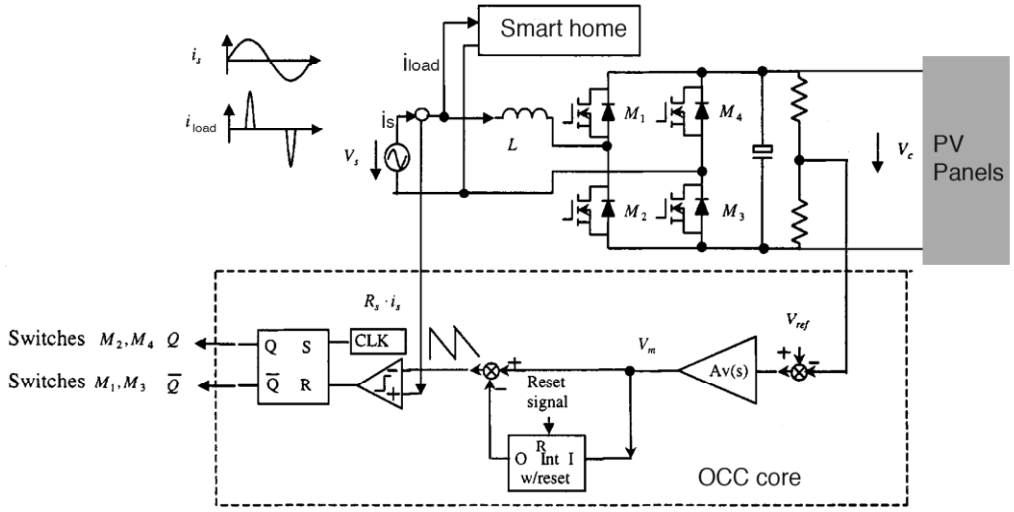


Figure 3 Printed circuit board for OCC-APF

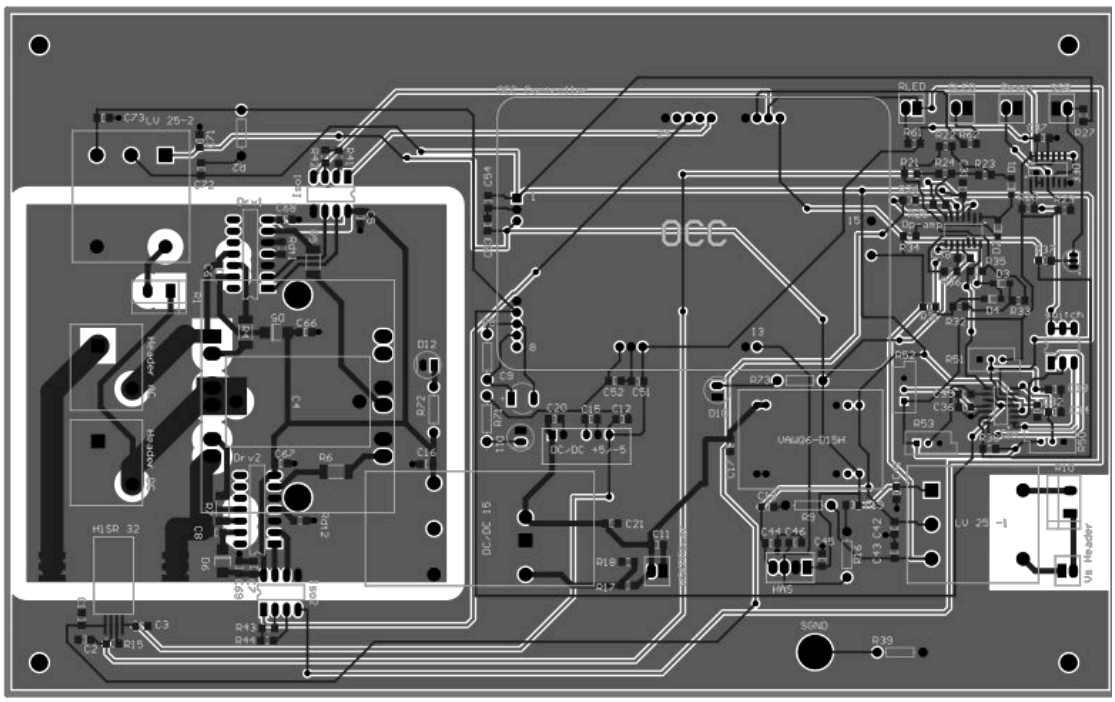


Figure 4 The OCC-APF Prototype, Left-Front view, Right-rear view



The OCC-APF prototype was first debugged and tested at laboratory. It was then delivered to UCD and was tested at a real world environment of test home. It went through a set of planned test procedures including eight scenarios:

- Lights
- Lights & Electronics
- Electronics
- Vehicle Charging
- Kitchen Appliances
- Vacuum & Air Compressor
- Whole House Fan, Water Heater & Vacuum
- Washer & Dryer

Following points were observations from the real world test.

- The APFC consistently adjusts power factor to very near unity, as predicted from our analysis.
- Reactive power is reduced by more than 80%, as predicted.
- The APFC reduces electric current drawn by the load, as predicted.
- Real power consumption increases – by 2-10%, as predicted. When the load is heavy, the real power consumption increases should be about 1-2%, when the load is near zero, the real power consumption increases should be about 100%.
- Current and real power consumption tends to be more stable when the APFC is enabled, as predicted.

The project has provided an excellent opportunity for my students to practice the knowledge they learned from classes and also experience many real world challenges that were not in any textbooks. My students Roozebeh Naderi, Weijian Jin, Yiming Ma, and Shijie Yu have worked closely on the circuit design, mechanical and thermal design, component selection, PCB layout, machine tool operation, circuit assembly, testing, and debugging. Dr. Taotao Jin, expert of

One-Cycle Control, Inc. has provided valuable assistance in the controller design and system debugging and testing.

Our team is ready to undertake the challenge to implement grid-tied inverter/APF combo as smart inverter for field demonstration.

CHAPTER 2
FIELD EVALUATION OF ACTIVE POWER FILTER

UC Davis managed and facilitated an in-field evaluation of the Active Power Filter system and the load signature monitoring hardware developed by UC Irvine. The evaluation was conducted in a 'smart home' residence in Davis CA. The home studied included many of the features evaluated as part of the modeling efforts within this project. Some of the leading energy features of the home included:

- Multi-function variable-speed air-to-water heat pump for heating, cooling, and Domestic Hot Water (DHW)
- Retrofit radiant heating and cooling
- Nighttime ventilation pre-cooling
- All LED interior and exterior lighting
- Electric vehicle charging
- On-site photovoltaic electricity generation
- Micro-inverters for photovoltaics

Results from the field study were analyzed to assess:

- Power consumption by the Active Power Factor Correction (APFC) device
- The extent to which power factor was corrected at the meter
- The impacts for real power, apparent power, current and reactive power

2.1 Project Background

2.1.1 Objectives

The overall goal of this task was to develop a clearer understanding about field performance of the Active Power Filter for correcting power factor. Specific objectives of this effort were to:

- Install and monitor the APFC device in a 'smart home' application
- Measure performance of the APFC in various operating states

Technical details about the Active Power Filter device are covered in a parallel report chapter; no additional explanation is necessary here.

Low power factor from end uses contributes to inefficiencies in grid scale electricity distribution, which can increase the size, cost, and maintenance requirements for grid infrastructure. Correction of power factor may also reduce primary energy consumption and greenhouse gas emissions for electricity generation by improving distribution efficiency. Power factor correction is not intended as a cost saving efficiency measure for end users, but it may be valuable for utilities, and for general public good, if it can reduce costs and environmental impacts from the electric system as a whole (Misakian 2009). The vision for power factor correction advanced by UC Irvine is appealing because it could be integrated with inverter hardware at a relatively low cost. This would allow solar homes to provide a benefit for power

quality on the grid, by correcting power factor for all loads in a home during all hours. Integration of this capability could reduce the size and cost of utility owned power electronics.

2.2 Methodology and Technical Approach

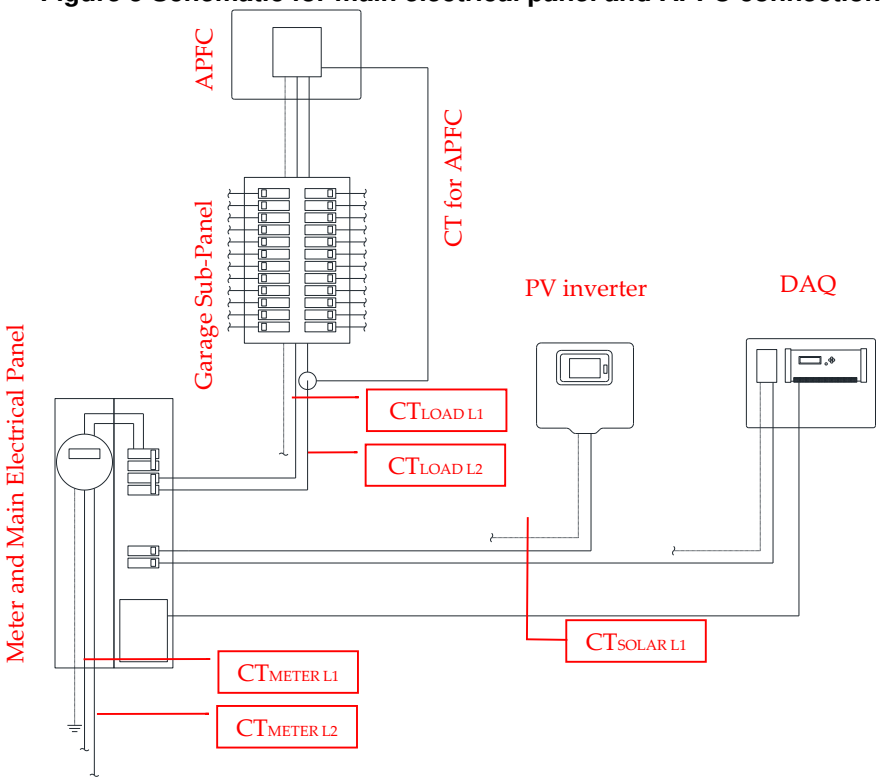
UC Davis installed a range of instrumentation and data acquisition in the smart home to monitor a number of electrical characteristics including:

- Electric Potential (*volts*)
- Current (*amps*)
- Real power (*kW*)
- Apparent power (*kVA*)
- Reactive Power (*kVAr*)
- Power Factor (*PF*)

These measurements were setup on each phase for multiple branches to separately monitor: all generation, all loads, and the metered grid connection.

Figure 5 illustrates the schematic arrangement of the electrical system for the home, along with the measurements installed. The Active Power Filter was connected to a single phase, and wired to inject current onto the bus between the meter and the breakers for each load circuit. Importantly, in order to operate correctly, the active power filter must measure current on the main line connection to the grid. The active power filter device uses this measurement in a control loop to adjust the input of current that corrects the power waveform. The control algorithm targets a power factor of unity measured at this point. Without such a current transducer, the device would have no feedback from which to make control decisions.

Figure 5 Schematic for main electrical panel and APFC connection



The APFC was installed for a period of two days, and was only allowed to operate while researchers were on site, actively observing performance and adjusting system operating parameters. Therefore, the results of this field study do not assess robustness and flexibility for the system. However, the results of this study do provide an assessment of real world performance for the device and proves the concept in a variety of operating scenarios.

2.3 Results and Discussion

2.3.1 Baseline Characteristics

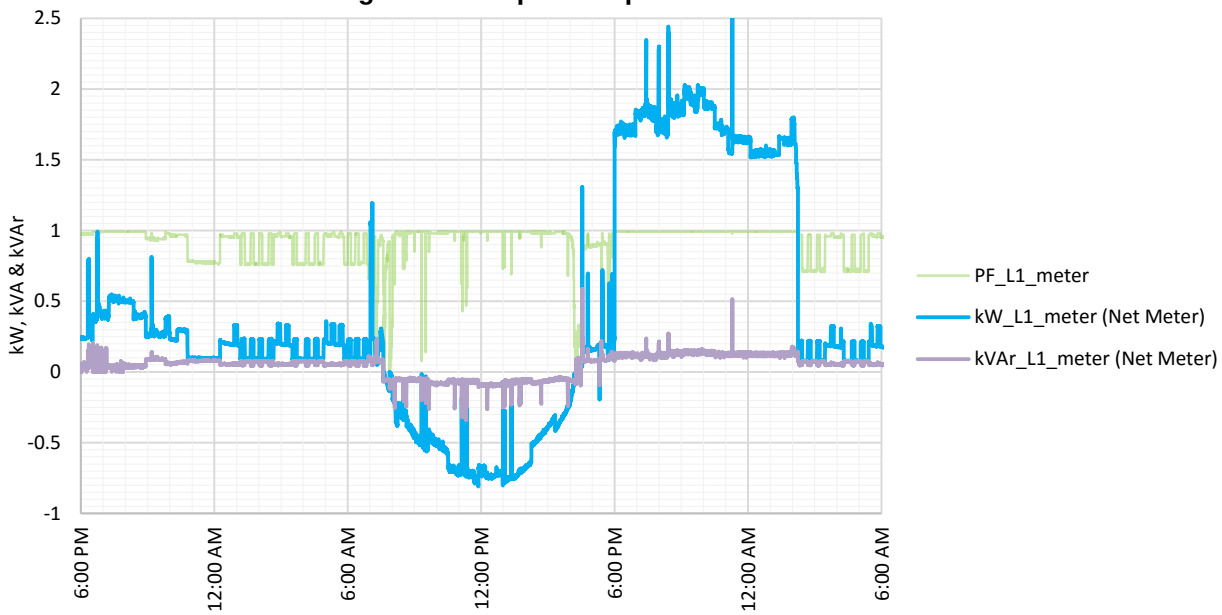
The smart home was monitored for several weeks prior to installation of the APFC in order to develop a baseline understanding of the home in regular operation, and to compare observations with modeling expectations conducted in a parallel task. **Error! Reference source ot found.** illustrates a typical load profile from one day during the baseline monitoring period in February. Review of this data provides the following key observations:

1. The load-generation profile corroborates model estimates for high efficiency ZNE homes.
2. The addition of electric vehicle charging tends to worsen the rate of change between generation and consumption, since vehicle charging almost always begins as soon as the occupant returns home. Shifting this load to later in the evening or charging more slowly could ease the dramatic shift between generation and load.
3. Power factor is worst during those periods when power generation nearly balances loads. In these periods, on-site generation provides adequate real power on average, but

the grid must still provide current for those portions of the power cycle where current from the solar does not balance current for the loads.

4. Power factor for some loads, such as vehicle charging, is nearly at unity. This occurs because certain modern electronics already incorporate power factor correction.

Figure 6 Example load profile from test home



2.3.2 Impacts of APFC:

The APFC was set up in the test home for two days and observed under a series of different load scenarios. The research team constructed each hypothetical load scenario by grouping different end uses. For each load scenario the team collected ten minutes of data with the APFC enabled, then ten minutes of data with the APFC disabled. This provided clear side by side comparison to assess the impacts of the APFC without the confounding variations and ambiguities that are present with typical use patterns. The eight scenarios tested included:

- Lights
- Lights & Electronics
- Electronics
- Vehicle Charging
- Kitchen Appliances
- Vacuum & Air Compressor
- Whole House Fan, Water Heater & Vacuum
- Washer & Dryer

Figure 7 15-second increment data for "Vacuum & Air Compressor" test with and without the active power filter

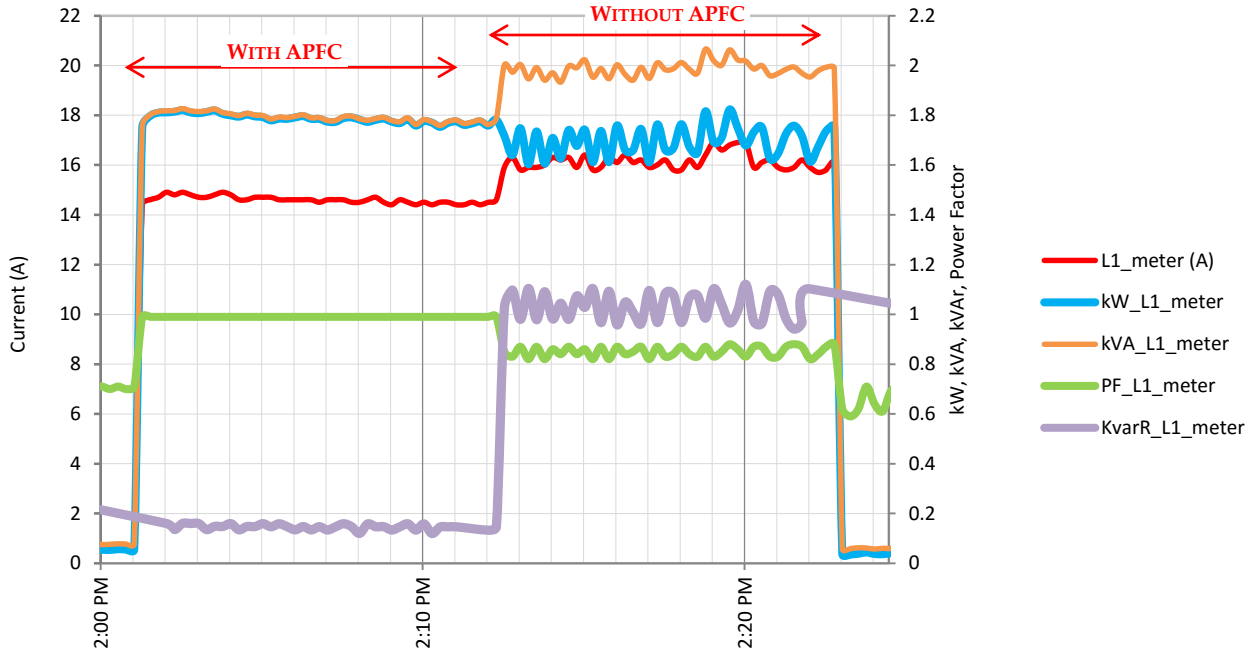
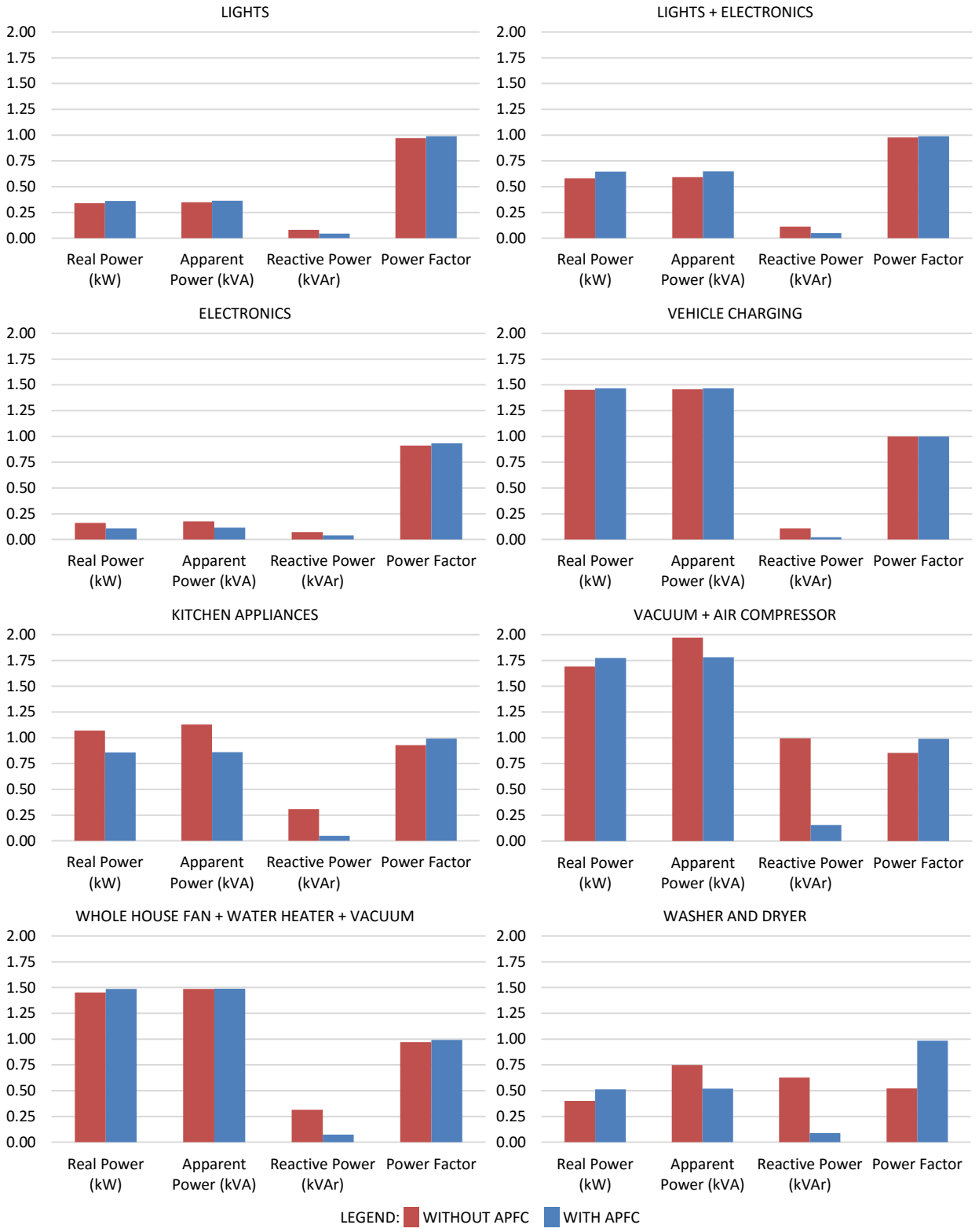


Figure 7 plots the data collected in one mode of operation ("Vacuum + Air Compressor") with and without the active power filter system. Similar tests were performed in eight different modes of operation with similar results. Review of the data reveals the following:

1. The APFC consistently adjusts power factor to very near unity.
2. Reactive power is reduced by more than 80%.
3. The APFC reduces electric current drawn by the load.
4. Real power consumption increases – by 2-10%
5. Current and real power consumption tend to be more stable when the APFC is enabled

Figure 8 Summary results for APFC tests in eight different modes of operation



These observations show that while the APFC improves power factor, it can also result in an increase for real power consumption. The reason must be one or both of the following:

1. The increase in real power is dissipated as heat through the APFC
2. The increase corresponds with an increased energetic output by the load

According to the APFC design team, the level of power increase observed is consistent with design expectations. The device has a fixed continuous power draw of about 20 Watts, plus a variable power draw that scales with the magnitude of reactive power reduced. For the "Vacuum + Air Compressor" case presented in **Error! Reference source not found.**, the APFC esulted in a power increase of 80-100 Watts while correcting a 1.7 kW load with 0.85 power factor. This increase in real power consumption will increase customer utility bills, and may increase on-site/user greenhouse gas emissions.

However, power factor correction is supposed to improve generation and distribution efficiency for the electric grid writ large, so any downside associated with real power consumption on site may be outweighed by the upstream benefits, as long as the upstream energy use for manufacture of the power factor device is low enough. Ultimately, the overall implications for overall energy consumption, greenhouse gas emissions, and for public costs surrounding generation and distribution is not clear and require further investigation.

Figure 8 presents a summary of results from eight separate tests conducted in the same manner as the test presented inFigure 7. **Error! Reference source not found.** charts the average value for eal power, apparent power, reactive power, and power factor with and without the active power factor, under each "condition" of operation. For some of the tests, there were variations associated with the cycle and operating patterns of different appliances. Therefore, the average values presented for real power consumption may not be attributed completely to the active power filter.

2.3.3 Synthesis

In all cases, power factor is improved to near unity. When processes are disaggregated for each condition of operation and compared directly, real power consumption increases in every case. This is true despite the fact the average power consumption in two measurement periods was lower. These two cases were scenarios where sub-systems cycled according to patterns that could not be completely controlled for the purposes of measurement, including:

- "Kitchen Appliances". This mode aggregated several time controlled cycles such as a dishwasher, coffee maker, refrigerator and microwave.
- "Electronics". This set included multiple televisions, stereos, and computers. Power for each of these systems is not constant. Changes related to battery charging, television and radio programming, and system startup may have all made caused differences.

Lastly, the reader should also note that auxiliary subsystems for the APFC device tested were powered externally. The power draw was measured for every scenario, and was always less than 3.0 watts. This auxiliary power consumption is not included in the increases depicted in

Error! Reference source not found.. . The research team also suggests that the losses that result n a real power increase observed could be reduced.

2.4 Conclusions

The in-field evaluation provided an on-the-ground snap shot of performance for the active power filter, its impact on power factor, current, and power draw at the meter. Several different operating scenarios were tested with combinations of various types of loads in the home, and across a range of power draw from 100 Watts to 1.75 kW.

In summary, we find that power factor correction performs quite well in every scenario tested. Even for power factor as low as 0.52 with non-linear waveform distortion, the device corrected power factor to 0.98. Concomitantly, reactive power was reduced dramatically, by 60 – 85%.

However, while power factor is improved, these tests also indicate that real power consumption increases simultaneously. It appears that this increase in real power consumption may be associated with internal losses for the device. Despite the increase in real power consumption, the improved power factor should have real benefits for utility infrastructure costs and management of grid reliability. There are four key benefits:

- Since the current delivered to the home decreases the required current capacity for distribution infrastructure can be reduced.
- Transmission losses are proportional to current so distribution efficiency will increase.
- Since power factor is improved at the end use, utility infrastructure to correct voltage droop resulting from reactive loads can be reduced.
- The device studied here corrects low power factor resulting from waveform displacement and from harmonics. Therefore, the burden for power quality management carried by substation power electronics can be reduced.

In these ways, ZNE homes with active power filter could provide distributed benefits for grid management, and would result in utility cost savings. Since thermal losses associated with distribution would be reduced, the technology could result in reduced greenhouse gas emissions. Future research should consider whether or not these benefits outweigh the on site increase in real power consumption.

CHAPTER 3:
Load Signature Analysis and Wireless Monitoring System

3.1 Electrical Characteristics Capture

3.1.1 Methodologies

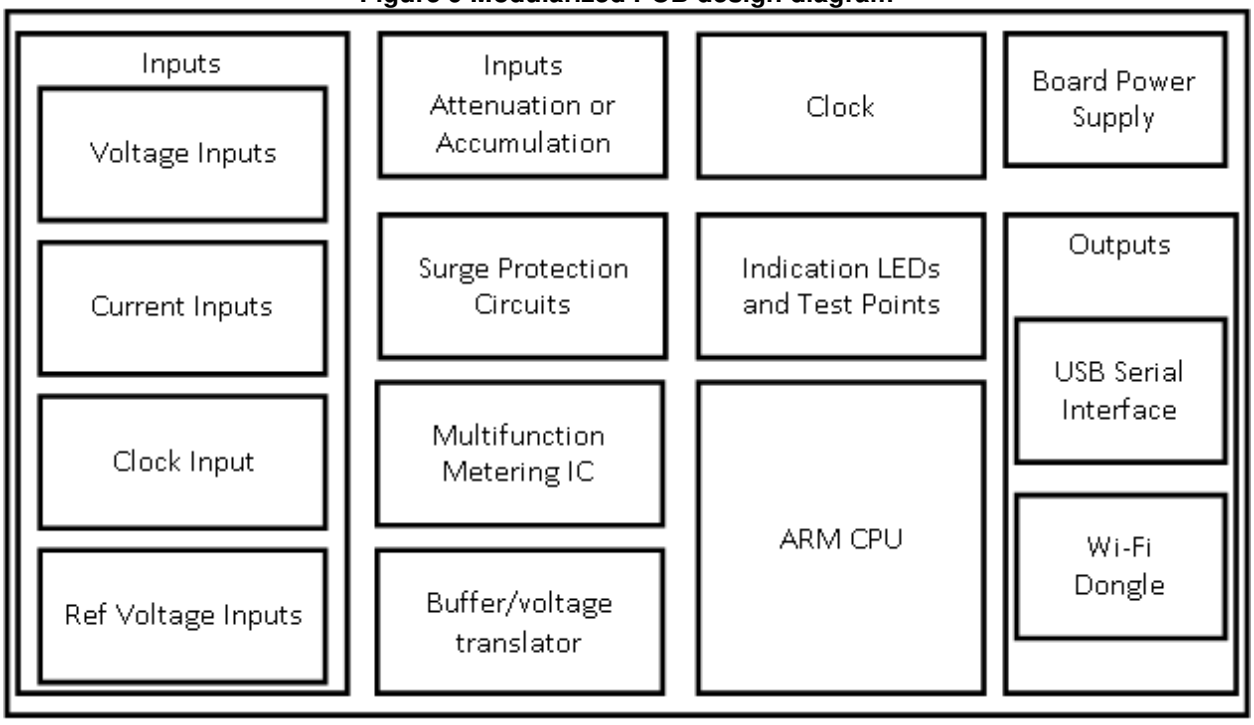
The load signature is captured by a printed circuit board (PCB) then passes the data to the gateway. The circuit design is consisted of two parts: passive sensing and analog to digital (ADC) conversion, and microcontroller level communications.

The board features fast sampling and ADC frequency capabilities given its compacted form factor. In order to obtain an accurate power measurement, voltage is measured periodically to calculate the power consumption overall. To measure the power factor (PF), the apparent, real and reactive currents are recorded for calculation.

3.1.2 Hardware design

The prototype is designed in a compact form factor with capabilities to be fit into the breaker box. For this demonstration purpose, the PCB is enclosed in a hard enclosure and directly plugged into an electric outlet to monitor a section of the house.

Figure 9 Modularized PCB design diagram



Voltage is directly fed to the PCB after attenuation circuits, whereas the current is probed with a coil and an integrator to obtain a current waveform by measuring the current with an inductor. Available methods of measuring current flow are: Rogowski coil and shunt resistor.

The shunt resistor will require a biasing point for system to measure current correctly. The system will require additional amplification either by op-amp or a voltage translator in order for the power meter IC to be able to read the current. By implementing this, it is very likely to be sensitive to noises from supply side, which can potentially be amplified with the actual current.

The current sensor determines the system's sensitivity. In our application, we used both an internal and external sensors. For enclosed current sensor (Rogowski coil part number: PA3202NL), is rated for 200A. This allows the system to measure the entire household including electrical vehicle charging at the same time, but the limitation remains for smaller devices, for example, idle phone chargers. These smaller power adapters usually draw a small amount of energy while plugged in but not used (also known as phantom loads). The current coil is not sensitive enough for picking up signals from such small loads. On the other hand, the system was also implemented for use with current probes. Tests have been conducted with Fluke current probes where the current probes are usually rated for 20A max with external battery power. The accuracy increased dramatically. System is sensitive for small loads down to approximately 1 watt. Therefore, more of smaller devices can be identified with more accurate current measurements. The drawback of the current probe design is such that the system requires multiple probing points in order to monitor the house as a whole. The accuracy comes at a price, where the coil's price is at a few dollars and the current probe can range from a few hundred dollars each.

Figure 10 PCB Schematics

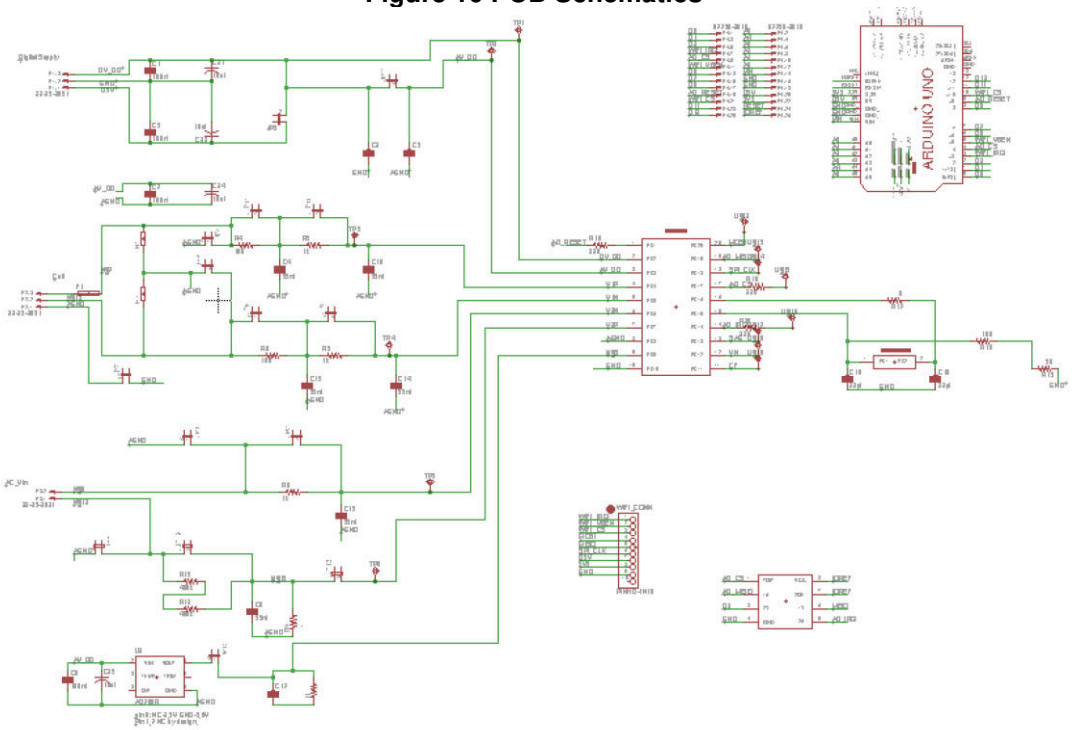
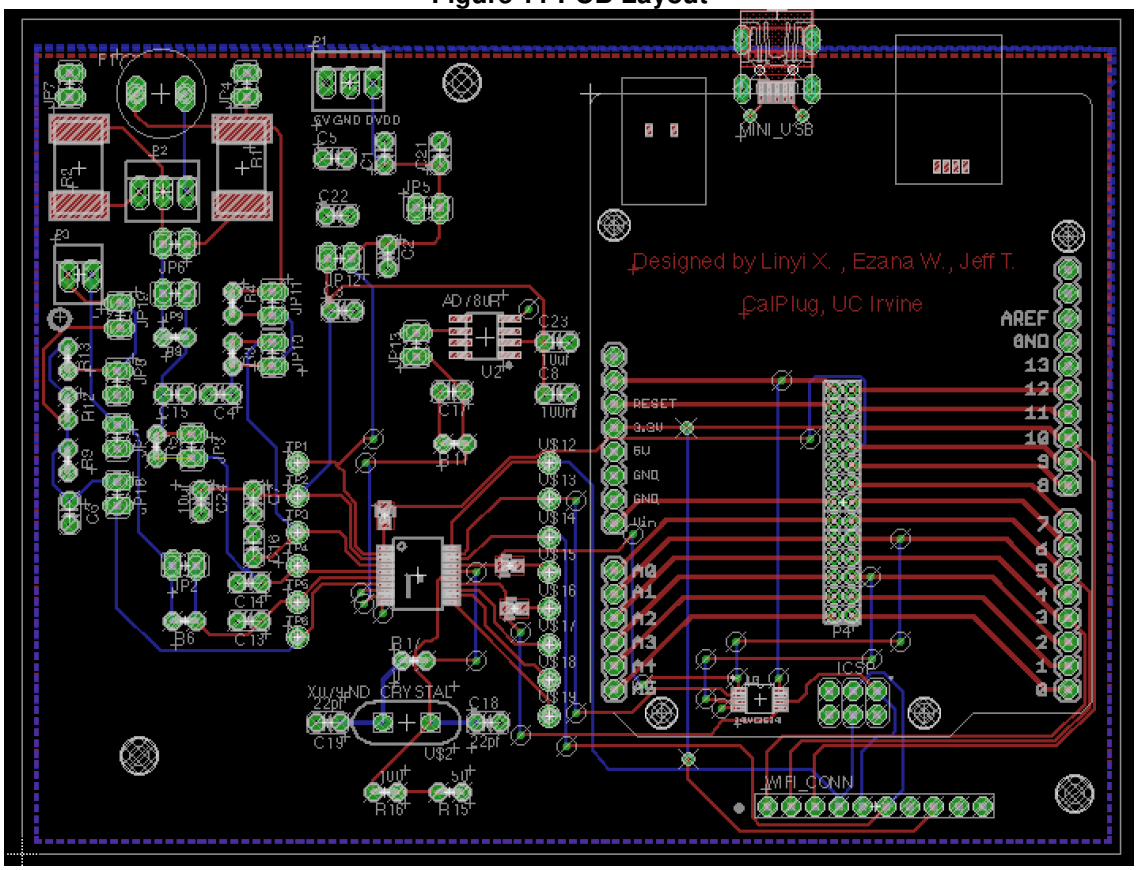


Figure 11 PCB Layout



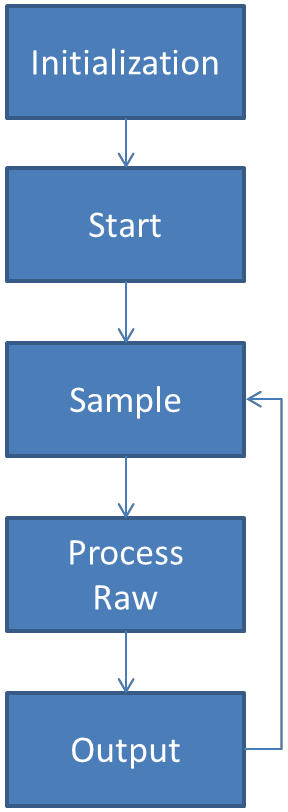
3.1.3 Firmware Design

The firmware is loaded on microcontroller level. The goal of the design is to have a quick response time from the physical device plugged into the grid to the device recognition completes. The system is designed in such a style with five main subroutines: Initialization, start, sample, process raw and output, illustrated as the figure below.

In order to accurately acquire the information needed for load disaggregation, steady–states data are taken in both power and power factor changes. This is the preliminary information needed to reaffirm the accuracy of disaggregation. The harmonic analysis is added on top of the steady state information. The steady-states analysis benefits simpler appliances better, which are more resistive. The harmonic analysis works better to identify non-linear loads. Other researches are also using transient state information to perform load disaggregation, which is the least effective of all three major approaches here. The greatest drawback of transient state analysis is its requirement for high sampling frequency, often beyond 500 kHz to 1 MHz. At the same time, the transient response requires the devices to have similar or almost identical transient responses in each test case. The limitation will be that this method can easily be inapplicable once expended to more devices of the same kind. For example, if a device is monitored under different ambient temperature, the results can also be different and hard to identify. Lastly, transient measurements will require a greater space of storage for device characteristics. In this design, we applied both steady state analysis and harmonic analysis in

combination. Therefore, the capture device should be able to measure voltages; power and power factor in a timely manner and perform basic data processing on the firmware level instead of relying on the gateway to process the raw data.

Figure 12 Implemented System Level Firmware Flowchart for ARM Processor on PCB



3.1.3.1 Initialization:

As the system starts up, it will run a self-check for Wi-Fi availability and attempt to connect over Wi-Fi. The system then initializes all variables and registers on the power meter IC, via 8-bit serial peripheral interface (SPI) communications. The system will initially report its IP address once connected to the Wi-Fi successfully. The disaggregation algorithm later uses this information to distinguish different zones of the house. The initialization will only run upon startup and reset button events.

3.1.3.2 Start

The system then starts sampling voltage and set the nominal voltages for the rest of the measurement then changes mode to measure current. The steady state voltage information will be stored as a baseline for power calculations.

3.1.3.3 Sample

The system samples up to 57samples per cycle, given that the grid supplies a 60Hz alternating current. Therefore, the sampling frequency can be adjusted up to 3420Hz. The system samples both real current and apparent current, voltage and reports power factor. Note, the system is capable of sampling at a higher frequency, but the development here aimed for real time ADC and processing. Therefore, the higher sampling frequency will require the

system to process at a faster speed, with more rigorous computing resources. We found that 3 to 3.5 KHz sampling frequency is sufficient to disaggregate devices and also process with an energy efficient Linux single board computer, as our gateway.

3.1.3.4 Processes Raw

The sample will be passed to the ARM processor via SPI. SPI ensures the high-speed communication between two embedded devices. The system processes the samples collected from the previous stage. Upon completion of analog digital conversion (ADC), the system then performs frequency domain analysis. The harmonic frequencies are: 60, 180, 300, and 420(Hz). Both phase and amplitude are evaluated.

3.1.3.5 Output

If the Wi-Fi connection was successfully established in the setup stage, the data will be communicated to the gateway via Wi-Fi. The Wi-Fi connection and data path are discusses in the next chapter. If Wi-Fi connection failed and serial cable is detected by the system, the system will send the data via serial communication at BAUD rate of 115200. Then the gateway will send the data to the server upon internet availability. Data can also be stored locally and uploaded at a later time.

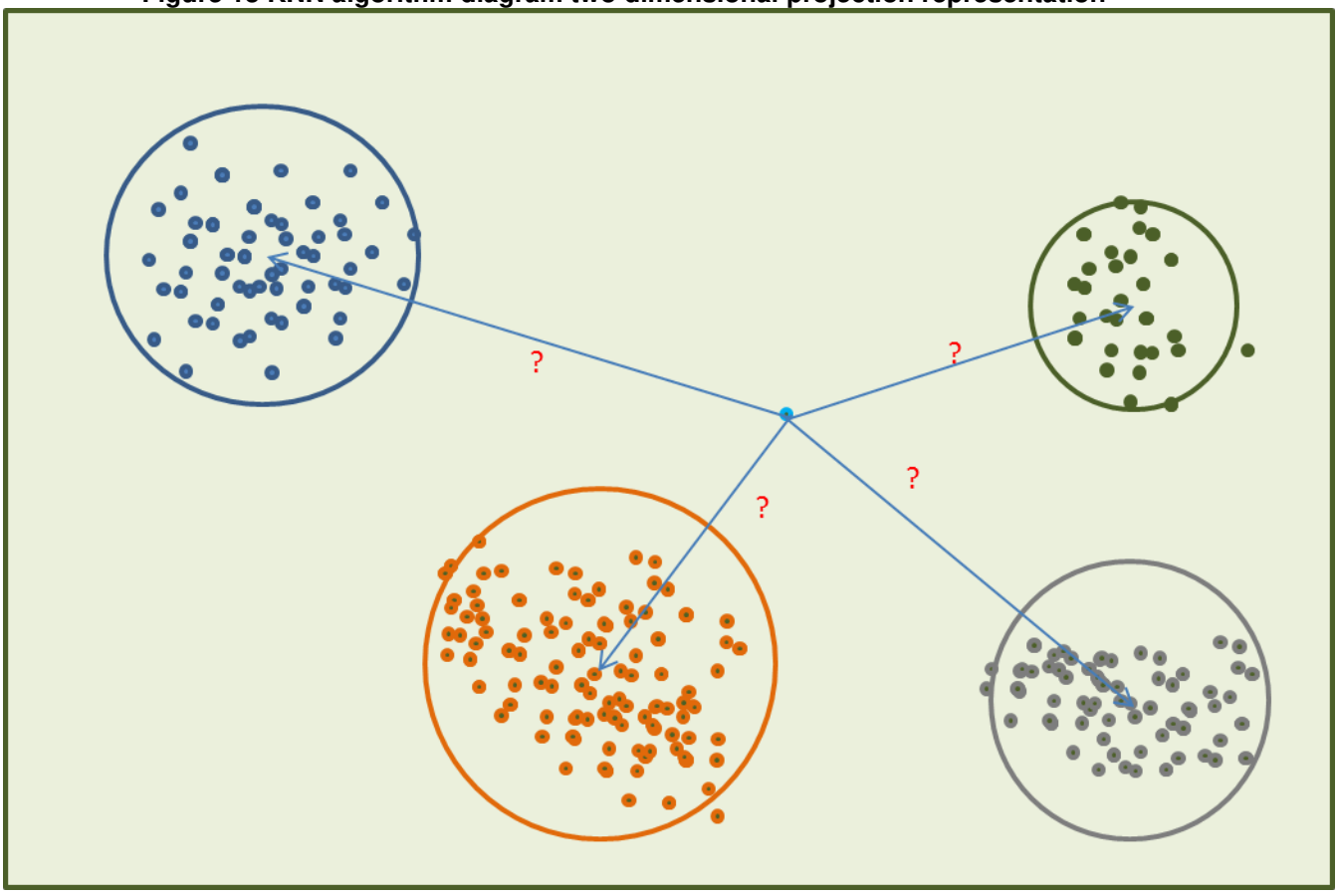
3.2: Disaggregation

Load disaggregation is a machine learning process, which requires a training period to first obtain data and targets. In this application, a supervised learning is chosen for more accurate classification. In order to have accurate and rapid responses, the system expands itself upon new entries into the database. Hereby, K-nearest-neighbor (KNN) method is chosen and modified and combined with a voting process instead of simple perceptron neuron network learning model.

3.2.1 Backward learning

The module will start with backwards learning. It will learn on the previous data if available. Hereby we use modified k-nearest-neighbor algorithm as a baseline algorithm to determine the most suitable device or category. From previously recorded data, the key features are extracted. Once key features are identified, heavier weights are assigned to these features.

Figure 13 KNN algorithm diagram two dimensional projection representation



The figure above demonstrates a basic version of KNN. Different data points are plotted on a 2D plane. Different data entries will form a cluster denoted by the color differences. Therefore, these entries forms a circular with a radius regards to the center of the circle. Upon new entries entering the dataset, distance is measured to all centers of clusters. The distances are ranked from shortest to longest, d_1; d_2... d_n. K denotes the number of nearest neighbor the algorithm is

supposed to evaluate. Once K is given, the first K results are taken, from the cluster that provides d_1, to d_k. The likelihood of new entry to be classified into each circle decreases as the distance increases. (Söder 2008)

In real life, the data can never be presented in 2D domain. For this project, each data entry is consisted of 11 features, therefore, to the 11^{th} dimensions. Some features are less valuable comparing to the others. The importance is taken into consideration when calculating the distance between the new entries to their neighbors. Most appliances will appear to have a dominant feature in one of the odd multiples of the base frequency, 60Hz. In this case, the harmonic values in this particular frequency are given a heavier weight in calculating the distance to neighbors.

3.2.2 Forward Prediction

Once training completes, the program runs forward as new data comes in. The program will classify the data into appliances. There is also a committee voting process on the criteria for KNN's consideration. For example, if the harmonic feature in one frequency domain appears to be dominant, this feature is assigned with a heavier weight when computing distance. The more dominant the feature is the heavier weight it becomes. Once the top features are identified, the distance between each entry is measure to the center of the clusters. The total weight is then ranked to find the closest clusters, which will be the identifier of the classification.

Once the system is trained, steady state data will be better to identify devices that have definitive power states or frequent usage patterns, such as light bulbs. This detects the sudden incremental or decline in power, in both active and reactive. KNN will identify the closest cluster to the device with its characteristics. Since power can be simply added together to verify the accuracy of the prediction, this can easily identify appliances with significant energy consumptions.

On the other hand, the non-linear loads are more difficult to identify. With the harmonic features, the data collection dataset size and time are both reduced. This allows the system to capture and perform raw process at the same time.

During forward prediction classification process, the K-fold cross-validation committee voting ensemble learning adds weight to different dimensions. The feature with greater correlation will be placed with a heavier weight comparing to the other ones. For example, table lamps will have a greater magnitude in 60Hz harmonic value whereas TV will also have a relatively significant harmonic value in 180Hz along with 60Hz harmonic values. Therefore, the 180Hz harmonic value is more meaningful comparing to 300Hz and 420Hz values. The weight of each committee member is pre-defined in the backward training stage, but only referenced by k-fold cross validation.

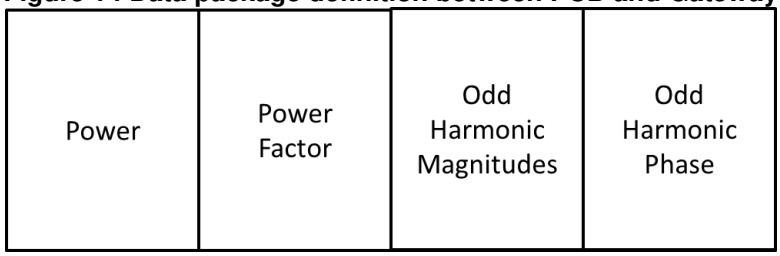
3.3: Communications

In order to achieve real time monitoring, devices have to be identified dynamically followed by display on the mobile interface dynamically as well. Hereby we define the communicational protocols between devices in this system.

3.3.1 PCB to Gateway Communication Protocol

The PCB is synced with the gateway every 2 seconds. Each message contains the power consumption in total, power factor, odd multiples of 60Hz harmonic features' magnitudes in digital counts and phase values in degrees. The KNN based algorithm later performs classification to processes these values.

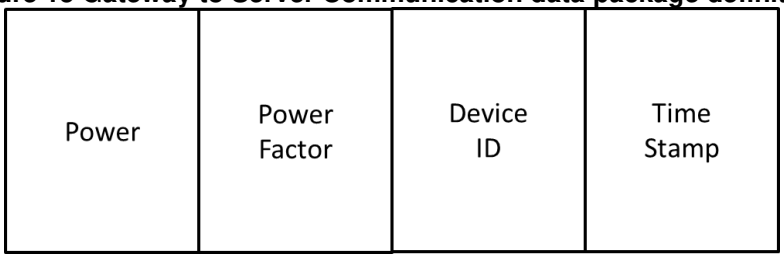
Figure 14 Data package definition between PCB and Gateway



3.3.2 Gateway to Server Communication Protocol

From the gateway, this data package is sent out upon availability. The server is capable to handle data insertions significantly faster than the physical devices sensing and classification speed. The time stamp is referencing the time the gateway received the input from the PCB, instead of the time of the server receiving the input from the gateway. By doing this, the timestamp will not need further correction upon internet unavailability. Whenever the internet becomes available, the data will be sent over the internet and inserted to the database.

Figure 15 Gateway to Server Communication data package definition



3.4: User Interface and Usage Modes

The interface provides the users with a simplified and unified overview of different areas of the house regarding its energy consumptions and power status. Data is stored on the server end for later analysis to understand the bigger picture for future usages. Once the time domain data is acquired, the system can also expand to evaluate time domain events as a signature in addition to devices' electric characteristics. This will even help to identify some devices which are normally hard to tell. At the same time, this will help to establish a baseline consumption model for the household. In the long run, this data can also be taken into consideration to set the stage for more accurate disaggregation.

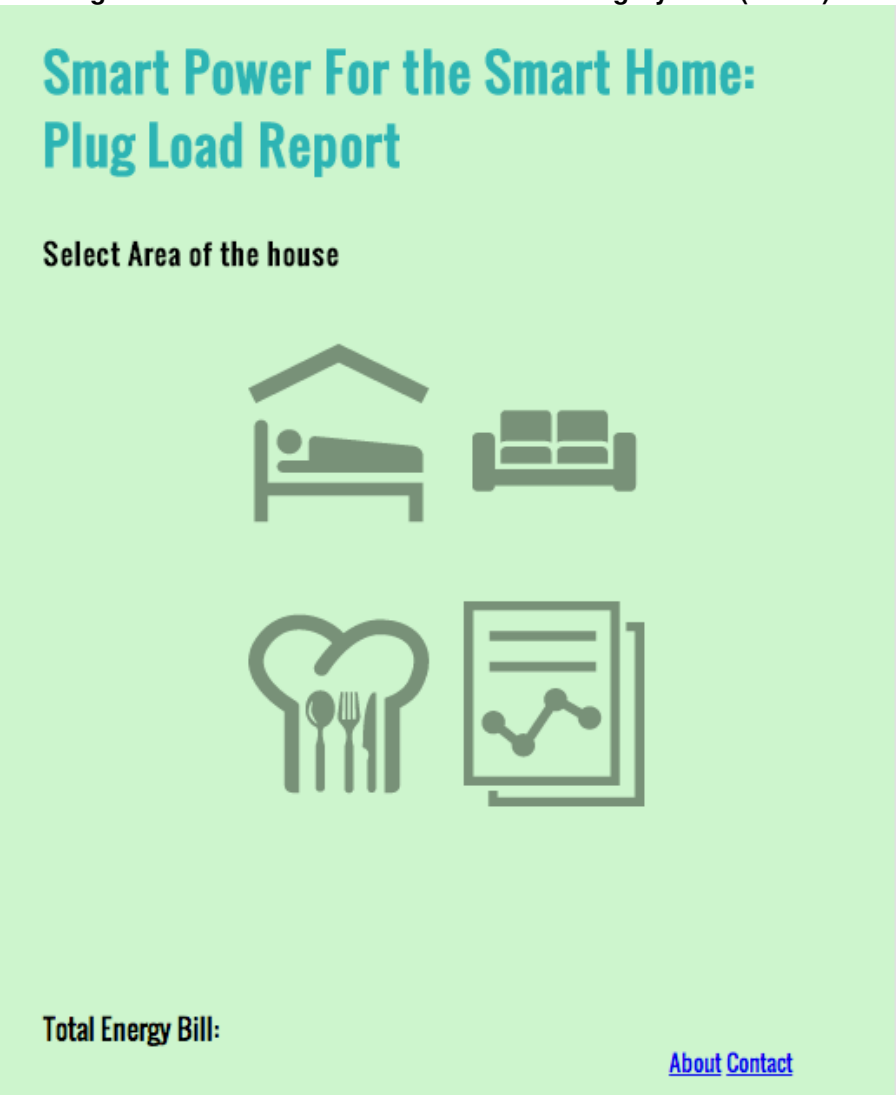
The user interface is designed with the elegance to provide a relaxing sensation to viewers where the general public may find data to be overwhelming and lose their interest in the monitoring system. Also, since data is hosted on a server, it allows future implementations to integrate an alert feature, where users can receive notification from abnormal energy related activities such as fire or outage.

3.4.1 Normal Operational mode

In normal operational mode, the system operates under forward prediction part of the algorithm. The system will continuously identify devices upon new events recognized on the board level. The events and data are displayed under each sub-area of the house. In this demonstration, the data is categorized into bedroom, living room and kitchen. The last icon is for entering the training mode. Users can simply click on a subsection of the house and view device connectivity status and power consumption. The user interface is expandable. The server stores much more information but only displays a small portion for simplicity. It might not be appropriate to display the full set of data for an average user but it has the back end capability to display more than just power consumption and device recognition results.

Another advantage of this design is: that it will feed back to assisting with load disaggregation. If multiple monitoring devices are at present in a household, the can disaggregate plug loads with a higher precision once they are assigned to an area. For example, most households will not have a TV in the kitchen, where living room is a more common place to appear. Or an electric stove will be very unlikely to appear in a bedroom setting. This will help the load disaggregation system to eliminate many possibilities, which may or may not contain a similar load signature.

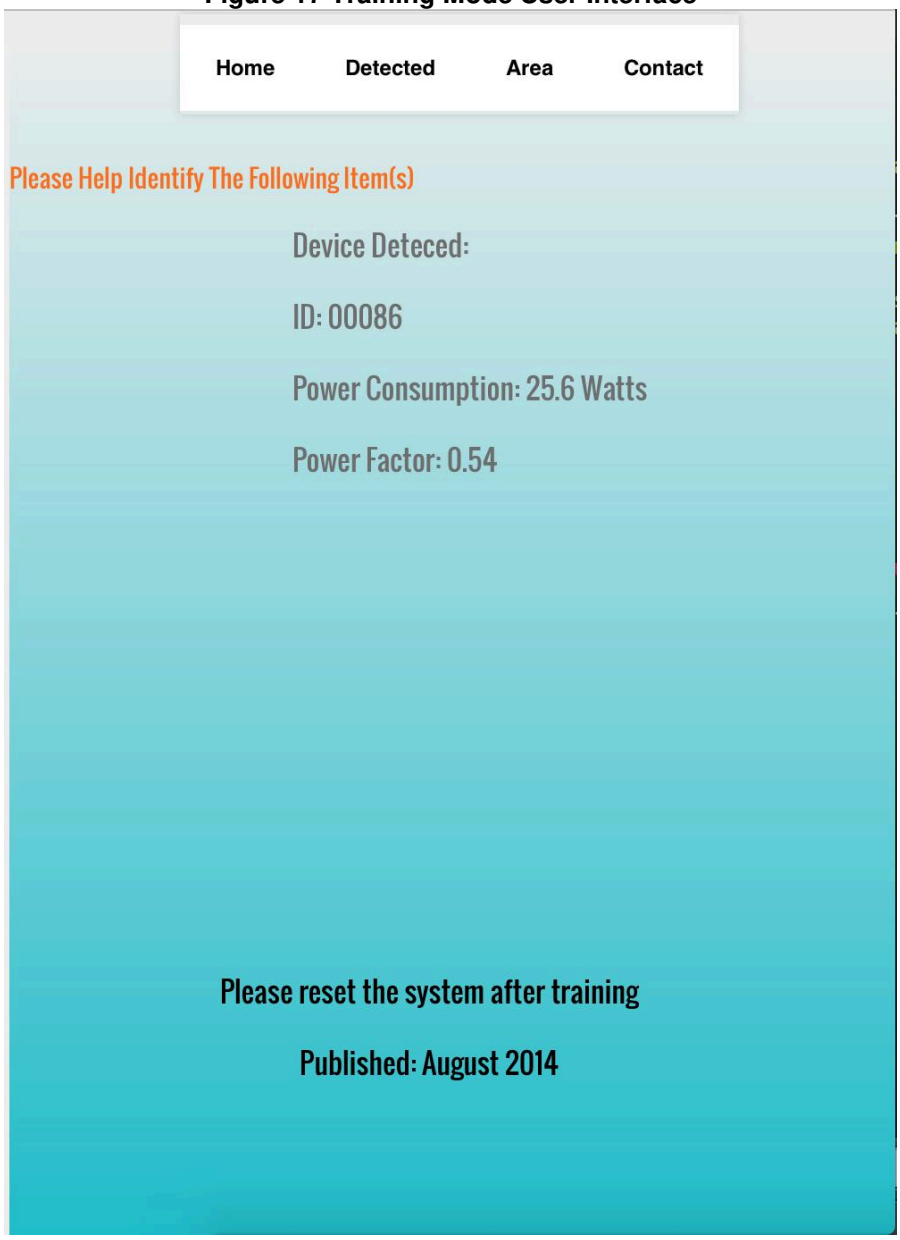
Figure 16 User Interface for Load Monitoring System (Home)



3.4.2 Training mode

When setting up the device, users can select the lower right corner icon to enter training mode shown in figure 7. In training mode, the system will start to detect the devices plugged in. One at a time, the system will record its electrical characteristics, even not displaying every single characteristic used for identification, but to just display the power consumption. Users can use this to roughly estimate whether the capture is accurate or not. Then the user should select one subarea of the house and add the device into that subsection of the house. Once the training is completed, the user can simply press the reset button on the PCB and return to "home" on this interface to normal operational mode, as Figure 16above.

Figure 17 Training Mode User Interface

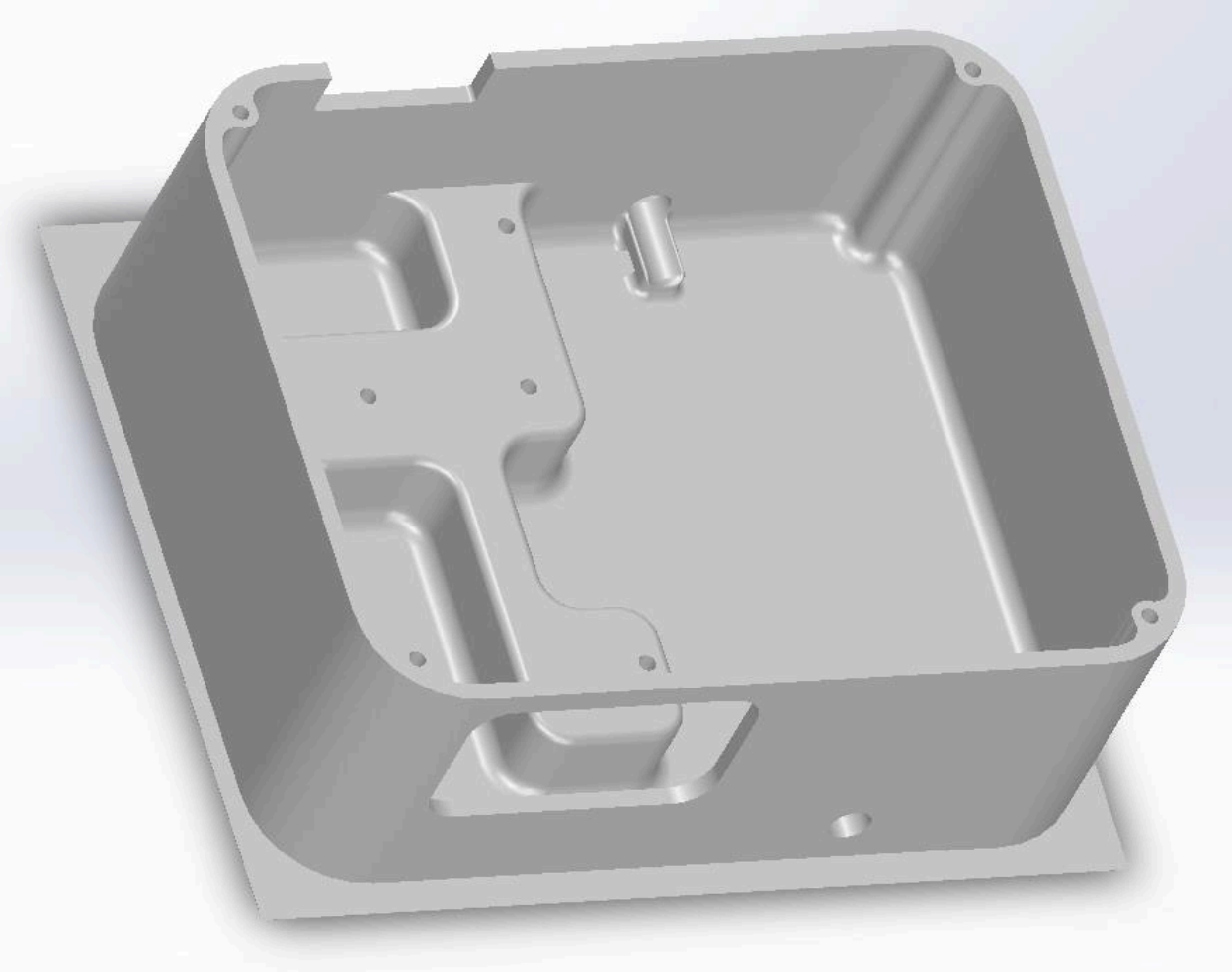


3.5: Industrial Design

In order for conduct in house testing, the PCB requires a few steps to package it to be a more consumer ready product. For both safety and usability, we have designed an enclosure for our electronic devices. The enclosure is designed such that:

- Protects the circuitries enclosed.
- Allows max airflow to keep board at a nominal working temperature without additional fans or heat sinks.
- The cables are placed on wire-guiding slots, which prevent the cables from falling out easily when the device is pulled by the cable.

Figure 18 Enclosure Interior

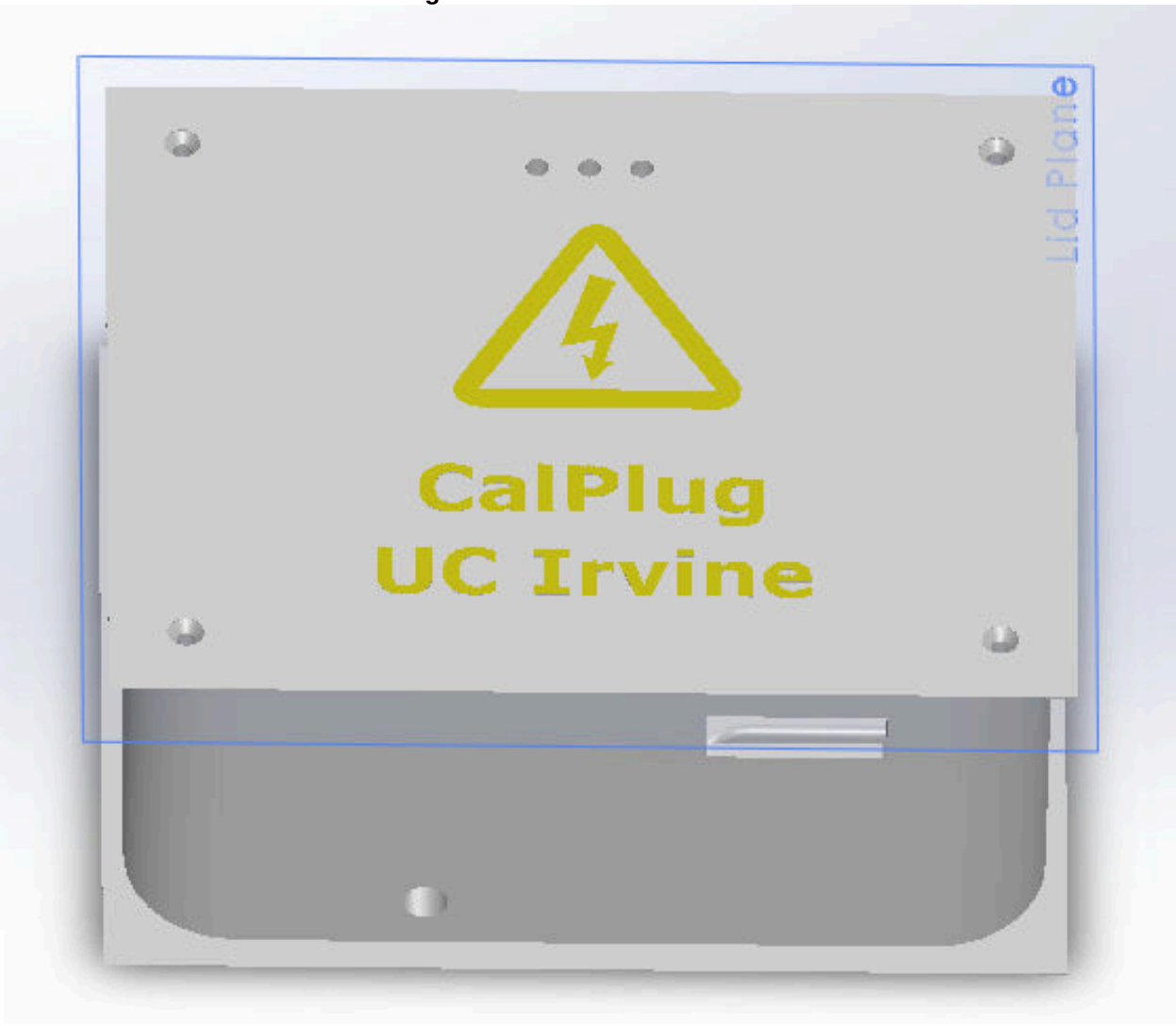


The device is designed in two pieces with the convenience of 3D printing. This eliminates the errors of alignment so that only one part of the box has to be reprinted. The top of the box has three holes for placement of the LED status lights. Once the box is closed, it would be hard to know the states of operation. Since the box will be left at a residential unit, it requires extra caution from the user once out of the lab controlled environment. The larger cutout is for the access to multiple USB cables to both supply power and data communication. The smaller

cutout is designed for the USB dongle to extend out of the box. Since the dongle has an onboard chip antenna, this would allow maximum signal strength.

The board is designed with latched cables to allow users to switch out coil to have a current probe installed for more accurate measurements. The user will have to simply unplug the current cable and plugin the current probe. A battery powered current probe is preferable.

Figure 19 Enclosure with lid on

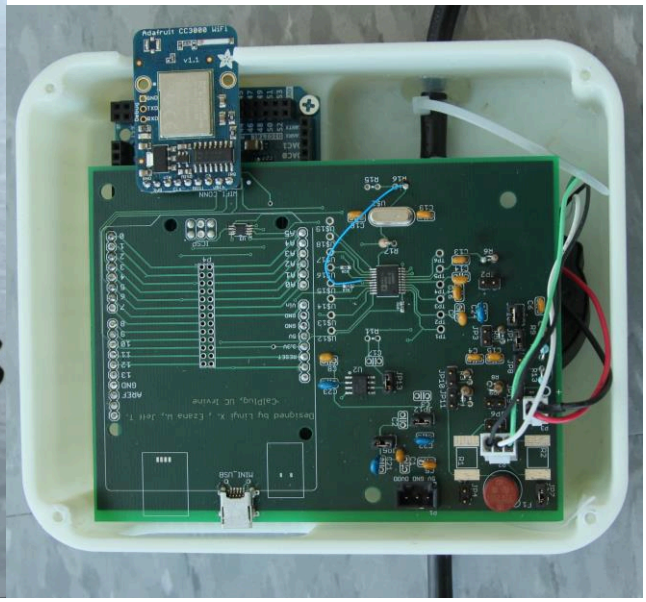


The pictures below show the finished product. The material glows in the dark so that once the users switch off the light, this will remain lit for a short period to ensure safety and visibility for both humans and pets. The Wi-Fi dongle operates on a 3.3V or 5V supply, which is 100% save for both humans and pets to make skin contacts, which is not recommended but is not life threatening if contacted by accident.

Figure 20 Finished Product pictures







The actual printed enclosure is highly durable and elegantly printed. The parts are secured and lose connections are highly eliminated. The housing for cables and coil help keep coil and wire in a fixed position so that the current flow sensitivity will not change due to the angle between the cross section of the coil and the hot wire. This will further help to improve the algorithm effectiveness by providing reliable sensing data at all times.

CHAPTER 4
INTEGRATED DESIGN AND CONTROL OF HVAC, GENERATION, AND STORAGE FOR MANAGEMENT OF LOAD PROFILES IN ZNE HOMES

4.1 Project Background

The Energy Efficiency Strategic Plan created by the California Public Utilities Commission (CPUC) in 2007 established the goal that all new residential construction should be Zero Net Energy (ZNE) by 2020. As a result of increased energy costs, global environmental concerns, and other factors, many homeowners and builders have begun investing aggressively in energy efficiency measures and on site solar generation. The resulting shift in the equipment, construction and occupant behavior in residential buildings is beginning to have an impact on the net-load profile seen by the electrical grid (Ref Cal ISO). This trend is projected to increase as ZNE homes become more common, and as a larger fraction of all generation is provided by on-site renewable resources.

The net-generation needs projected for California has a small peak in the morning, a lull throughout the day when solar resources are available, and a peak and the late afternoon. This trend emerges mainly from the fact that electrical output from solar resources declines at the same time that on-site demand from end-uses increases. The major difference between today's net load profile and the net-load profile projected for 2020 is the rate at which demand shifts. As the net-load profile evolves in this way, grid management will be challenged by three new conditions:

- Rapid changes in start-up and shut-down of conventional generation resources
- Over-generation risk as load changes more quickly than generator response
- Decreased frequency response when fewer conventional generators are available

ZNE residences typically have a net-load profile that *worsens* these emerging grid management concerns. The typical ZNE residential load profile is characterized by a small peak in energy demand in the morning, a substantial amount of generation throughout the day, and a sharp peak in demand in the afternoon and early evening. The net-load profile for ZNE homes, and for the whole California grid changes in highly significant ways throughout the year – the most important concerns about dynamic grid management are projected to occur in the spring and autumn.

Apart from technical challenges associated with rapid generation response and power quality on the grid, the projected change for the net-load profile will increase the cost of generation and distribution infrastructure Most importantly, since conventional power plants must be maintained in reserve to service electrical demand when renewables are not available, the utilization factor for these systems will decrease substantially, while their fixed costs will remain nearly the same. In concept, on days when a conventional gas fired power plant might currently operate for 16 hours, in a future scenario output might be constrained to 6 hours.

Projections for the California electricity environment in 2020 anticipate that 33% of our annual energy consumption will be serviced by renewables, but the required peak electrical output from conventional generators in the summertime will remain nearly unchanged (Rothleder 2013). Although solar generation is highly coincident with the cooling loads that currently drive peak demand, total electrical demand is projected to increase somewhat, so that the resulting peak in net-demand will be roughly equal, but later in the day than the current peak.

A uniform net-load profile would result in the smallest requirement for conventional nameplate generation capacity and the largest utilization factor for generation infrastructure. This scenario shouldn't necessarily be a strategic target, since it may not result in the overall lowest public cost, nor the least environmental burden. However, the currently projected net-demand scenario is also problematic. The most strategic path forward will likely include major changes in the way that electricity is used, generated, and stored.

The study reported here develops a better understanding of how ZNE homes will contribute to net-loads on the grid, and considers how different residential efficiency measures might benefit or aggravate the emerging concerns about grid management.

The study used modeling and simulation to explore how a variety of options for mechanical equipment efficiency and building construction practices affect the net-load profile for ZNE homes. One of the major considerations surrounds the impacts of a move toward all-electric homes. The efficiency measures simulated are mostly incremental improvements for conventional heating, cooling, and hot water systems such as increased building envelope insulation, and increased equipment efficiency. Changes for lighting efficiency and miscellaneous electric loads were not modeled – the primary focus was to understand how probable changes in mechanical system efficiency will affect the net-load profile for ZNE homes.

Although there are a variety of emerging specialized solutions that could serve as effective strategies for load shifting in residences, this study mainly explored the range of scenarios that conventional home builders, and building efficiency standards, are most likely to adopt in the near term when targeting ZNE. Future research should use the results of this study as the 'projected baseline' to determine the value of more specialized strategies. For example, more aggressive time of use rates could motivate changes in occupant behavior and system controls. However since current rate structures mainly incentivize homeowners to use less energy overall, this study focused on some of the most accessible near term methods to do so. Lastly, simulations also explored the ways that on-site electricity storage could shape the net-load profile for ZNE homes. The results highlight the fact that simple battery storage schemes currently utilized could actually worsen net-load profiles.

4.2 Objectives

The project was structured around three major objectives:

- Model the effects that energy saving technologies have on the net-load profiles of ZNE single family residences in California.

- Identify approaches that could beneficially shape the net-load curve.
- Develop recommendations for how residential design standards could lessen the emerging concerns about grid management as the fraction of renewables increases.

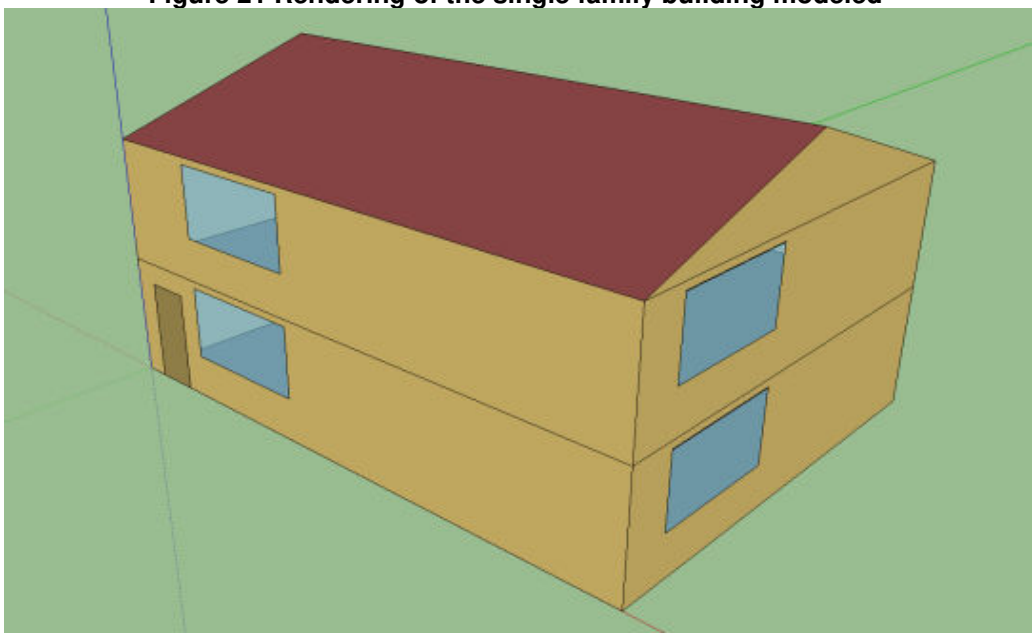
4.3 Methodology and Technical Approach

EnergyPlus was utilized for this parametric simulation effort because it integrates modeling of the building envelope, weather, HVAC equipment, internal loads, onsite solar generation and onsite electric storage in a single software package.

The research team developed an EnergyPlus model for a baseline single family residence with 2,400 ft² of conditioned space and 1,200 ft² of unconditioned attic space. The geometry of the building was based on a reference model published by PNNL (PNNL 2013); a rendering of the home is shown in **Error! Reference source not found.**. The model does not represent a articular home nor does it attempt to represent an average of all homes. Instead, it is designed to be an example of a "typical" home that meets all current California Title 24 construction standards.

Occupant behavior varies significantly from home to home. In order to simulate energy use for a 'typical' home, the research team developed an annual set of hypothetical daily load profiles for lights, equipment, and miscellaneous electric loads that resulted in aggregate annual distribution of end-use energy intensity that agreed with published data for single family residential buildings, including California's Residential Appliance Saturation Survey (KEMA 2010, Commonwealth of Australia 2012).

Figure 21 Rendering of the single family building modeled



4.4 Simulation Parameters

The research team conducted a parametric analysis of several different measures to characterize their impact on load profile for the home in every day of the year. Details for each measure are summarized in sections 4.4.1 – 4.4.8.

4.4.1 Insulation

Insulation for the baseline model was configured to comply with current Title 24 requirements: an R-value of 16 for exterior walls and an R-value of 38 for ceilings. In addition to the Title 24 compliant levels, the parametric modeling effort considered two incremental improvements to the level of insulation. A scenario representing 2 x 6 wall construction with fiberglass batt insulation was modeled with an R-value of 20 for exterior walls and an R-value of 50 for ceilings. A scenario representing a double thickness 2x4 wall with blown cellulose insulation was modeled with an R-value of 30 for exterior walls and an R-value of 60 for ceilings.

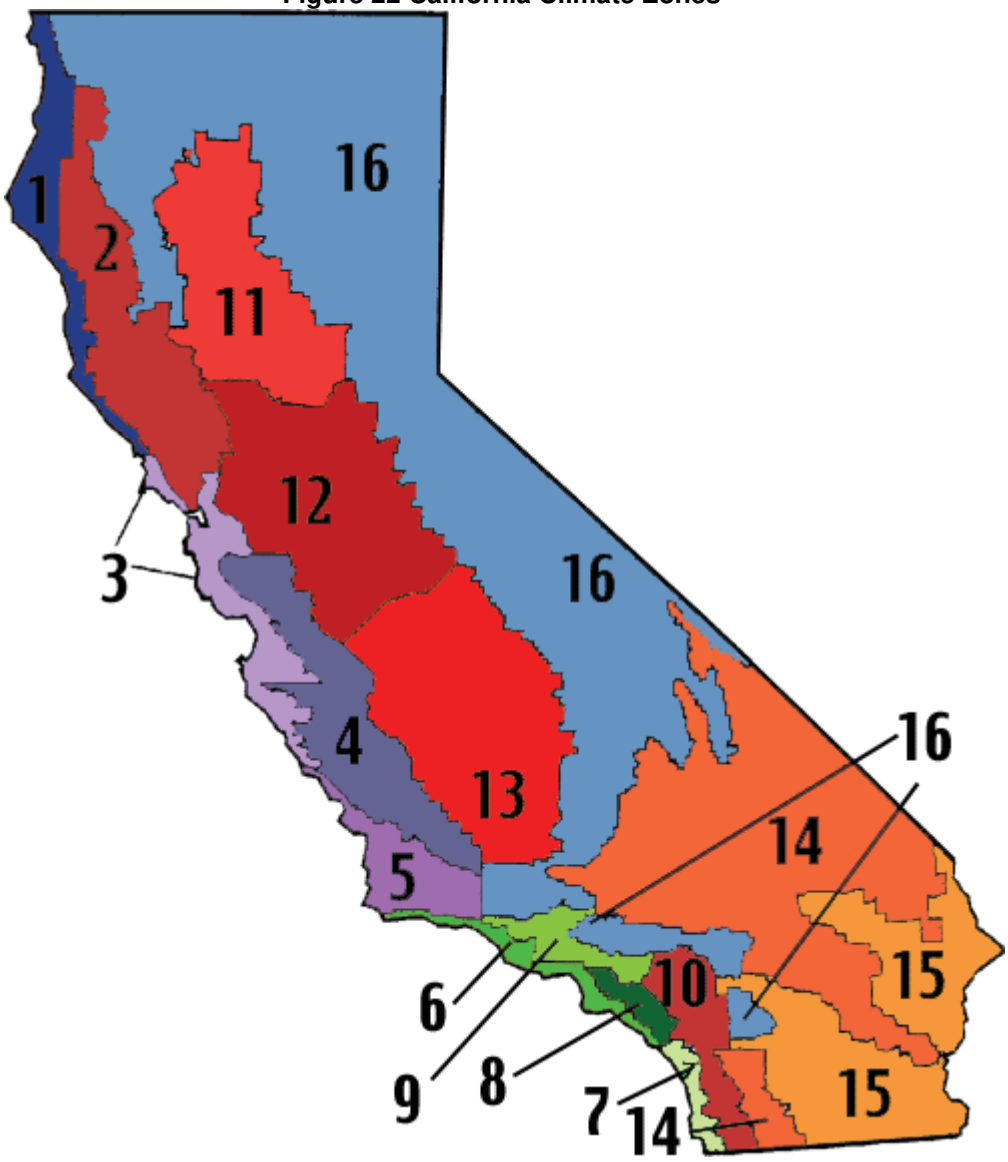
4.4.2 Thermal mass

The thermal mass of a building affects how much energy is necessary to cause a change in temperature and provides a buffer from ambient swings in temperature. This can affect the load profile by changing when and for how long the cooling and heating equipment must operate to maintain indoor setpoint temperatures. Two scenarios were considered to simulate performance with different levels of thermal mass. A typical thermal mass scenario was modeled to represent drywall construction, and a high thermal mass scenario was modeled to represent concrete block construction.

4.4.3 Climate zone

California is divided into 16 climate zones as shown in the map in Figure 22. The climate zone can have a large effect on thermal loads, on the performance of HVAC equipment, and on the amount of on-site solar electricity generation.

Figure 22 California Climate Zones



The Sacramento area (California Climate Zone 12) was use for the parametric simulations presented because it has a hot summers and cool winters – whereas some California climate zones are mild year round. Select parameter sets were simulated in all 16 climate zones to explore the effect that climate zone has on the performance of the building.

4.4.4 Energy Source

Natural gas is widely used in California for cooking, heating, hot water, and clothes drying. Accordingly, the baseline model included a gas furnace for space heating, a gas water heater, a gas cooking range and a gas clothes dryer. However, a number of factors are driving a shift toward electrification for all appliances. In particular,

- There can be significant capital cost savings for ZNE developments without natural gas

- High efficiency electric appliances can have lower operating costs than gas appliances when powered by renewable sources.
- The potential for greenhouse gas reductions is severely limited if the main source of heat in a home is from fuel combustion. The same is true for reduction of other combustion emissions.

Therefore, models were developed for a home with all electric appliances and equipment. In the all-electric cases the house was modeled with an electric heat pump for house heating, an electric heat pump water heater, an electric cooking range and an electric resistance clothes dryer.

4.4.5 Mechanical efficiency

National standards require a minimum efficiency for vapor compression systems including air conditioners and heat pumps. In California, split systems are required to have a minimum Seasonal Energy Efficiency Ratio (SEER) of 14 and a minimum Energy Efficiency Ratio (EER) of 12.2. For heat pump heating, split systems are required to have a minimum Heating Seasonal Performance Factor (HSPF) of 8.2. Water heaters are required to meet a minimum energy factor (EF) based on their size and which is determined based on a 24 hour test. As of April 2015, electric water heater EF will range from 0.95 for water heaters below 55 gallons, to 1.97 for those larger than 55 gallons.

In EnergyPlus the efficiency of vapor compression systems is defined by a Coefficient of Performance (COP) at rated conditions. Both the EER and the HSPF are easily converted to a COP. Equation 1 describes the conversion from EER to COP and Equation 2 describes how to convert HSPF to COP.

$$COP = \frac{EER}{3.41214}$$

Equation 1

$$COP = \frac{HSPF}{3.41214}$$

Equation 2

Thus the national standards result in a minimum COP for split systems of 3.6 for cooling and 2.4 for heating.

In EnergyPlus the performance of the heat pump water heater is defined by the COP of the heat pump at rated conditions and the loss coefficient. The loss coefficient is defined as the heat power lost to the ambient air per degree Kelvin in temperature difference between the tank water and the ambient air.

Three different levels of mechanical efficiency were modeled for the home. The baseline case meets the national standards with a cooling COP of 3.6 and a heating COP of 2.4. The baseline heat pump water heater was defined with a COP of 2.4 and a loss coefficient of 5 Watts per degree Kelvin. For the higher efficiency cases, the COP for cooling was increased to 4.4 and 4.8

(EER of 15 and 16.4) and the heating COP to 3.2 and 3.8 (HSPF of 11 and 13). The improved performance is consistent with high efficiency systems such as the LG LAU/LAN series, the Fujitsu RLFCC series and the Panasonic Inverter series heat pumps. Improvements to the hot water heater were modeled with COPs of 3.2 and 3.8.

4.4.6 Loads

The electric loads in a single family building typically include a heater, air conditioner, supply fans, ventilation fans, water heater, clothes dryer, clothes washer, dishwasher, refrigerator, indoor lighting, outdoor lighting, cooking range, microwave oven, television, computer and miscellaneous plug loads. Additionally, some houses include an auxiliary heater, auxiliary refrigerator, auxiliary freezer, pool heater and pump, and spa heater and pump. The modeling efforts focused on equipment found in typical homes and did not consider the additional loads resulting from optional equipment.

The load profiles for most systems are dependent on weather and occupant behavior. The operation of HVAC equipment was controlled by EnergyPlus to maintain the indoor air temperature at a set point of 78°F for all cooling days, and a set point of 68°F for all heating days (the only exception was for cases with nighttime ventilation cooling). The load profiles for equipment that are dependent on occupant behavior were based on the Residential Appliance Saturation Survey (RASS) published by the CEC (KEMA 2010), the Residential End Use Monitoring Program (REMP) published by the Commonwealth of Australia, and other published data.

The RASS describes the annual energy use for different types of residential buildings, and breaks the aggregate annual values into several key end use categories. **Error! Reference source ot found.** through Figure 25 show the average annual energy consumption for single family residential buildings. For homes that use both electricity and gas, **Error! Reference source not ound.** and Figure 24 show the average annual electricity consumption by end use category for electricity and gas respectively. Figure 25 shows the average annual electricity consumption for homes with all electric appliances and equipment.

Figure 23 Annual electric end uses for a mixed energy single family building (RASS)

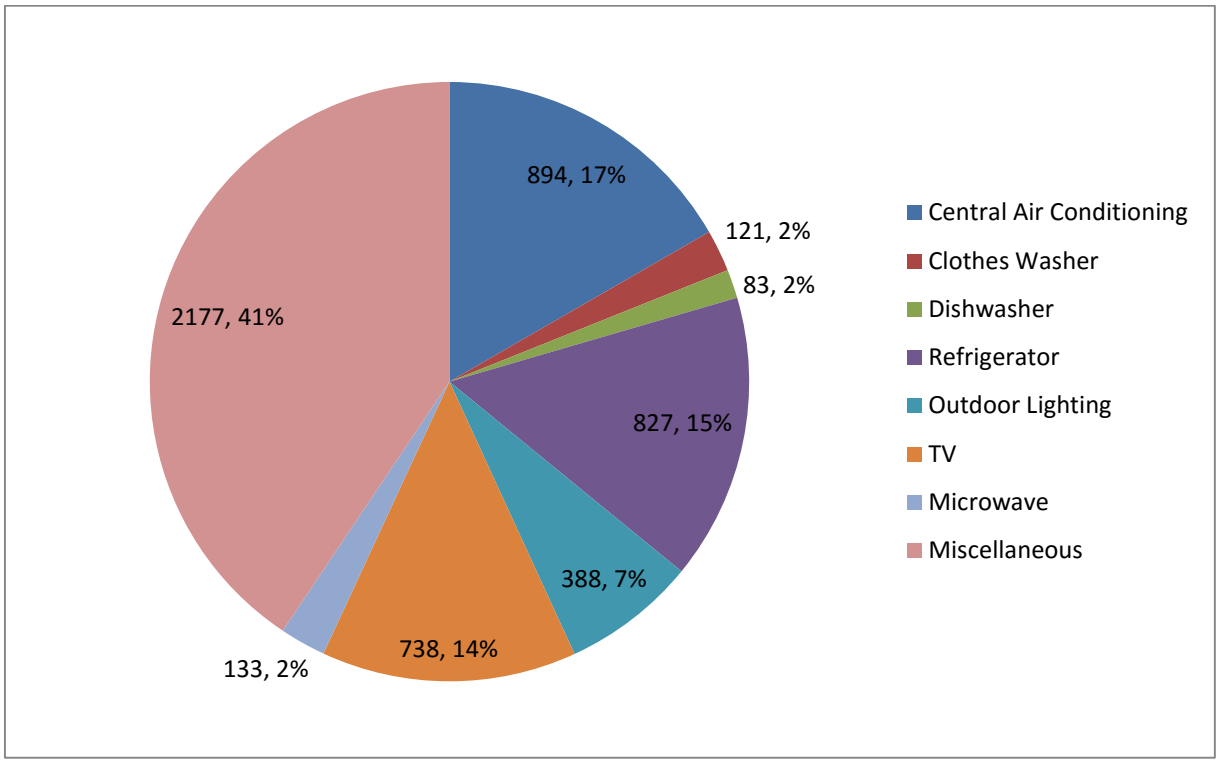


Figure 24 Annual gas end uses for a mixed energy single family building (RASS)

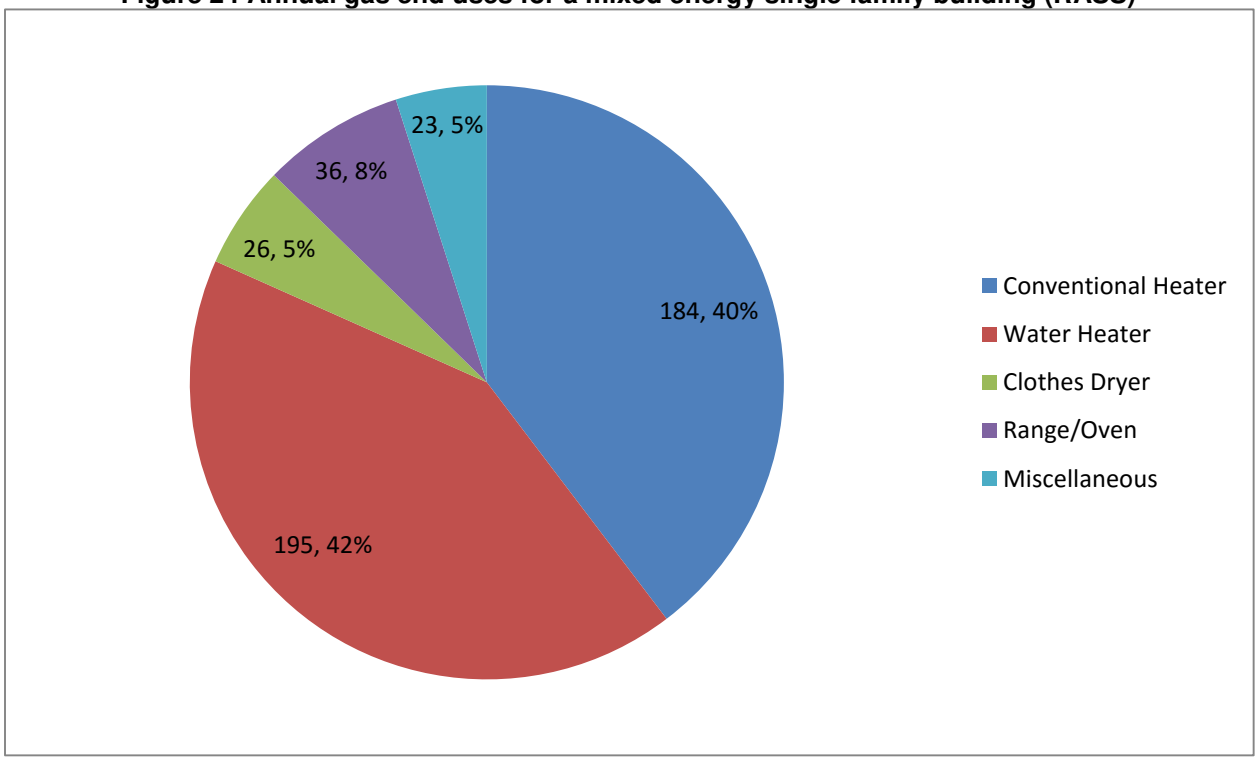
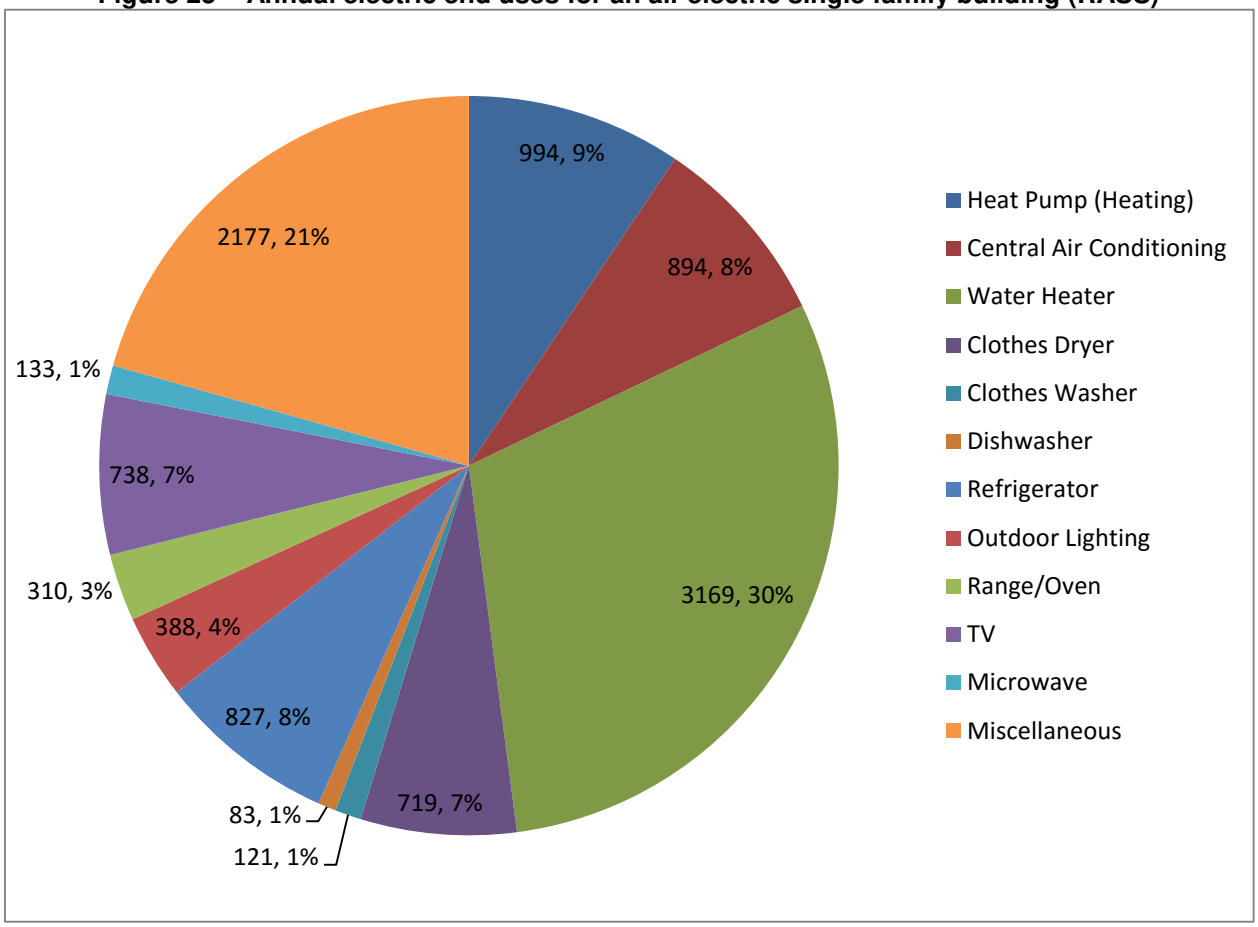


Figure 25 – Annual electric end uses for an all-electric single family building (RASS)



The research team developed hypothetical daily appliance load profiles that represent typical behaviors and that result in the annual energy use distributions that are reported in the RASS. Figure 28 shows one 24-hour net load profile for all non-HVAC equipment and appliances. The load profiles shown in Figure 26 and Figure 27were used for every day of the year with the exception of the clothes washer, clothes dryer and dishwasher. According to the US EPA EnergyStar program, the typical household uses the clothes washer, clothes dryer and dishwasher four times per week (EPA 2015). Therefore, to achieve load profiles that are consistent with typical behavior these appliances were operated once on every Sunday, Tuesday, Thursday and Saturday.

Figure 26 – Daily electric load profiles for non-HVAC equipment and appliances

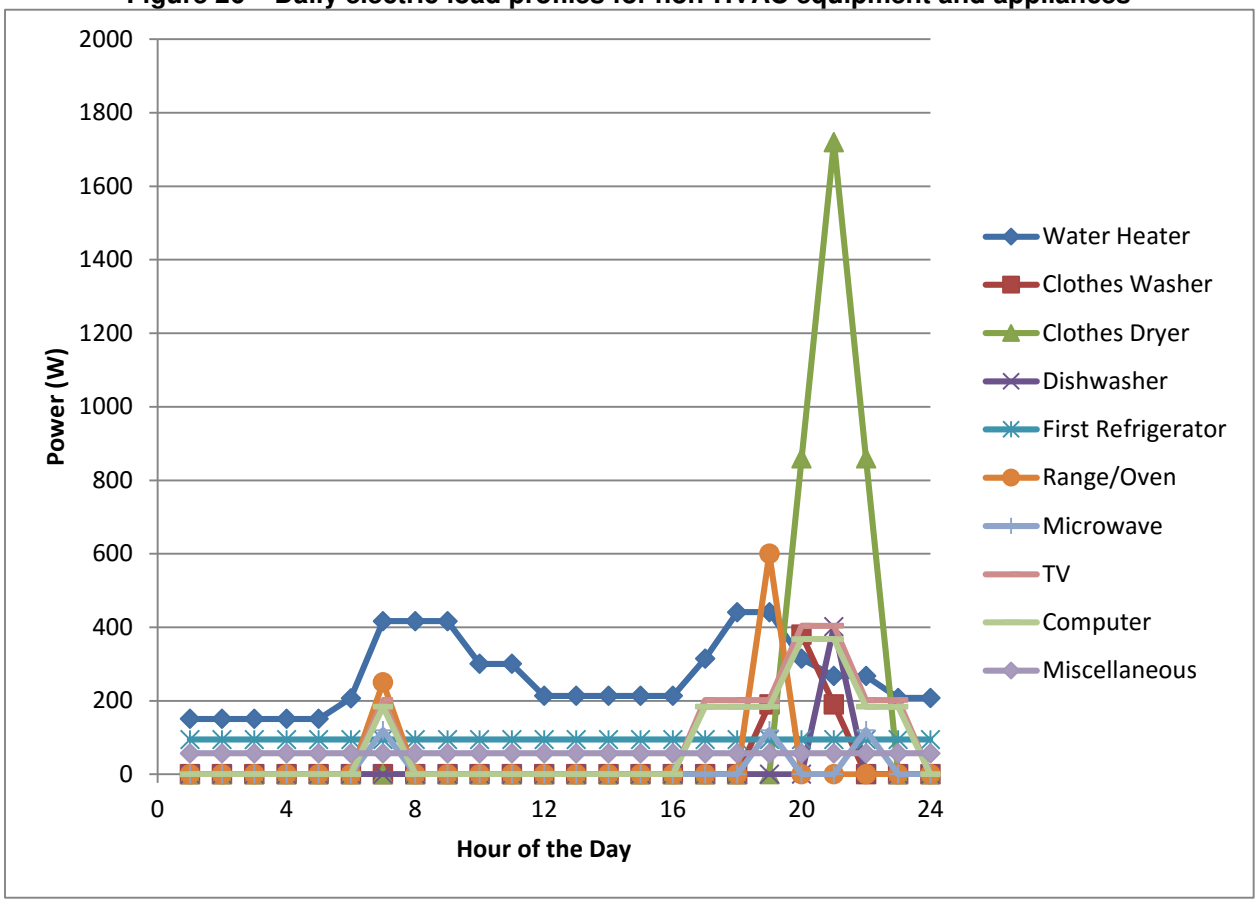


Figure 27 Daily gas load profiles for non-HVAC equipment and appliances

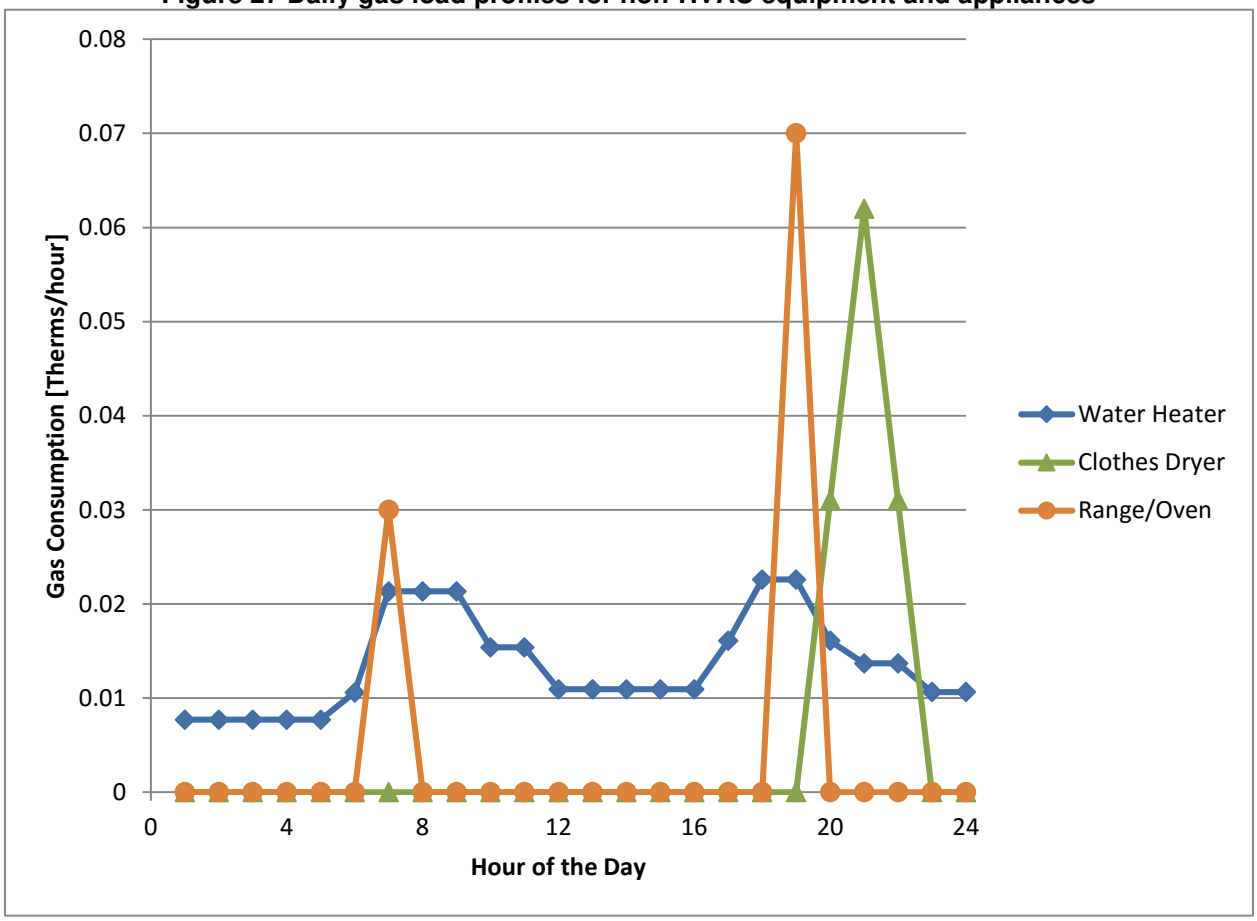
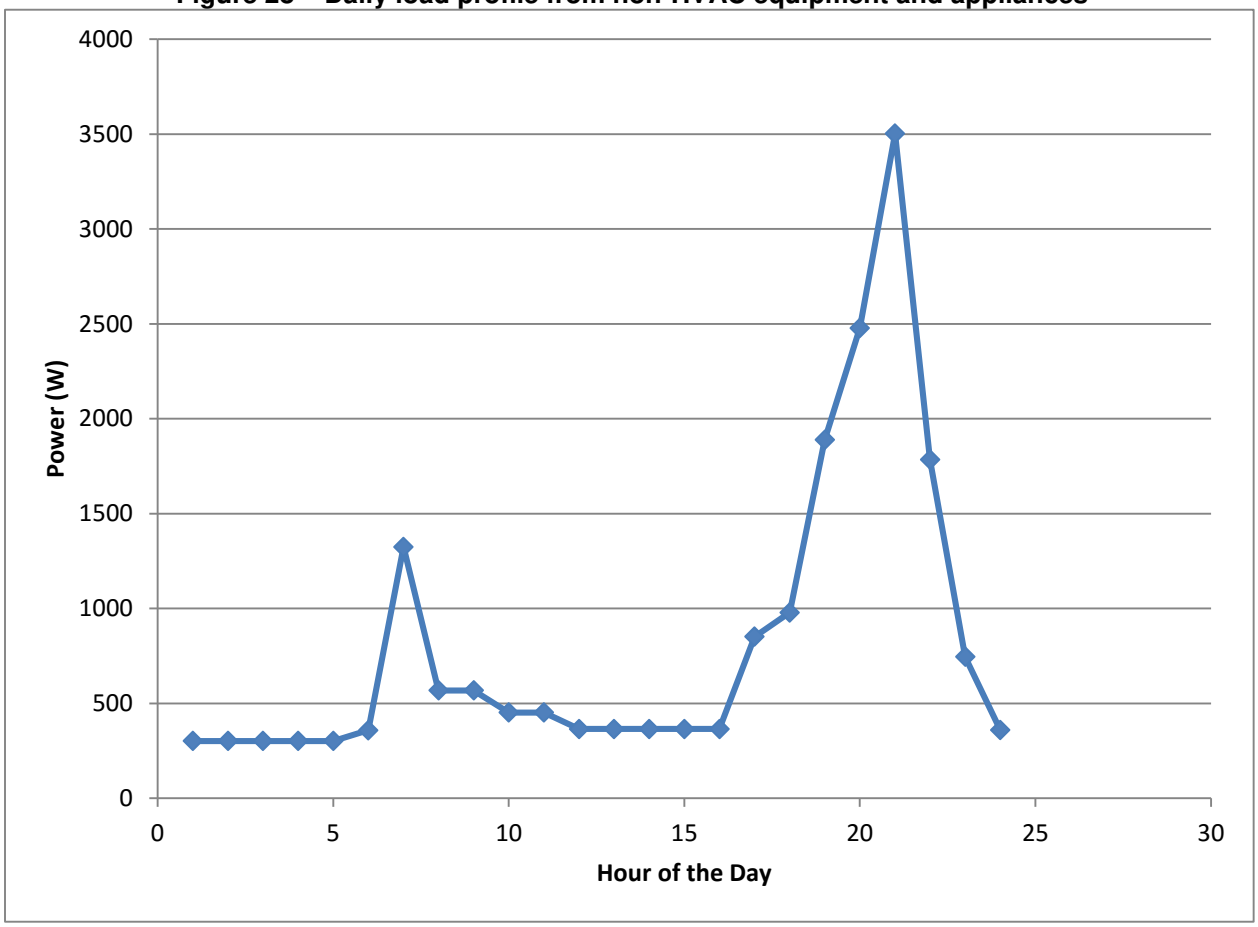


Figure 28 – Daily load profile from non-HVAC equipment and appliances



The water heater energy use profile is a special case because performance of this system is dependent on ambient conditions during operation and on the hot water use profile, which is dependent on occupant behavior. This is especially the case with the heat pump water heater since its efficiency and capacity are dependent on evaporator inlet air temperature. EnergyPlus was used to model the performance of the hot water heater based on ambient conditions and a hot water use profile developed from data published in the Commonwealth of Australia's Residential End Use Monitoring Program (REMP). The REMP monitored hot water use for five single family residential buildings in Australia over the course of one year, and published seasonally averaged, 24 hour use profiles. Figure 29 shows the normalized hot water use profiles published in the REMP. Although there is considerable variability in occupant behavior for different homes, the profiles all have two consistent peaks; one in the morning and one in the evening. The normalized hot water use profiles were averaged and scaled for our model such that the resulting annual energy use from a natural gas water heater would approximately agree with the annual energy use reported in the RASS. The resulting water use profile is shown in Figure 30.

Figure 29 Normalized residential hot water use published in the REMP by the Commonwealth of Australia

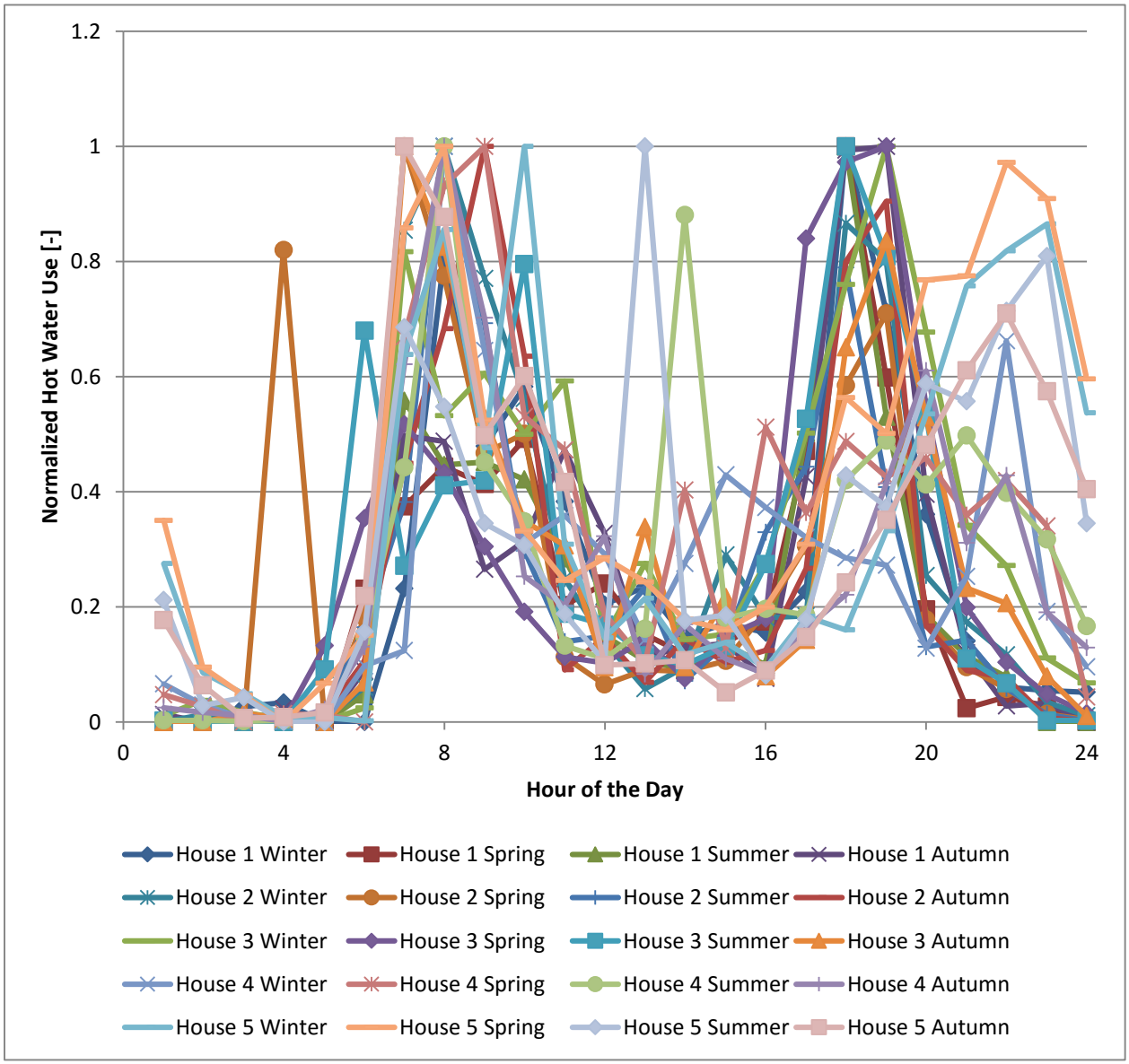
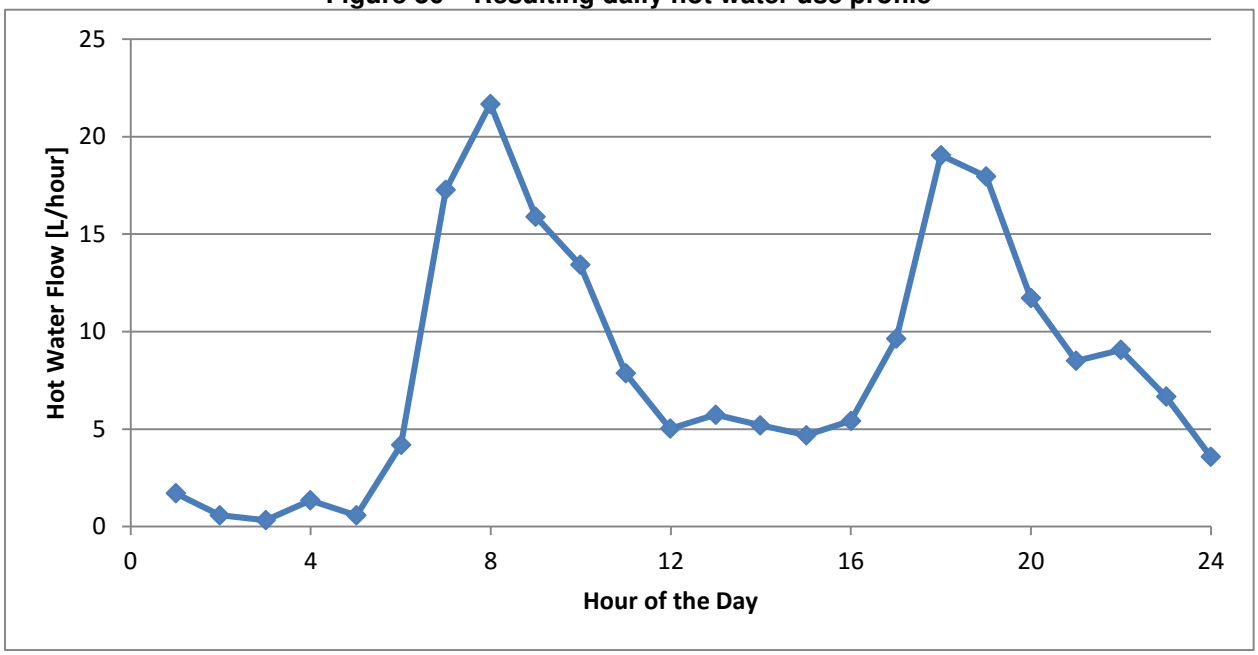


Figure 30 – Resulting daily hot water use profile



As Figure 30 shows, the daily hot water profile has two peaks; like the electricity load profile, one peak in the morning and one peak in the evening. Unlike the electricity profile, however, the larger peak in the hot water use profile occurs in the morning.

4.4.7 Onsite solar electricity generation

To define the performance of the onsite solar electricity generation in EnergyPlus a building surface, panel area and efficiency are specified. All solar panels were modeled on the south facing roof with a rated efficiency of 15%. The solar panels were sized for each simulation based on what would be required to achieve zero net annual electricity for that particular case. As a result, ZNE homes with more efficient systems were modeled with less solar capacity. In addition to a baseline scenario with no onsite solar electricity generation, three different capacities were modeled with 75%, 100% and 125% of zero net electricity.

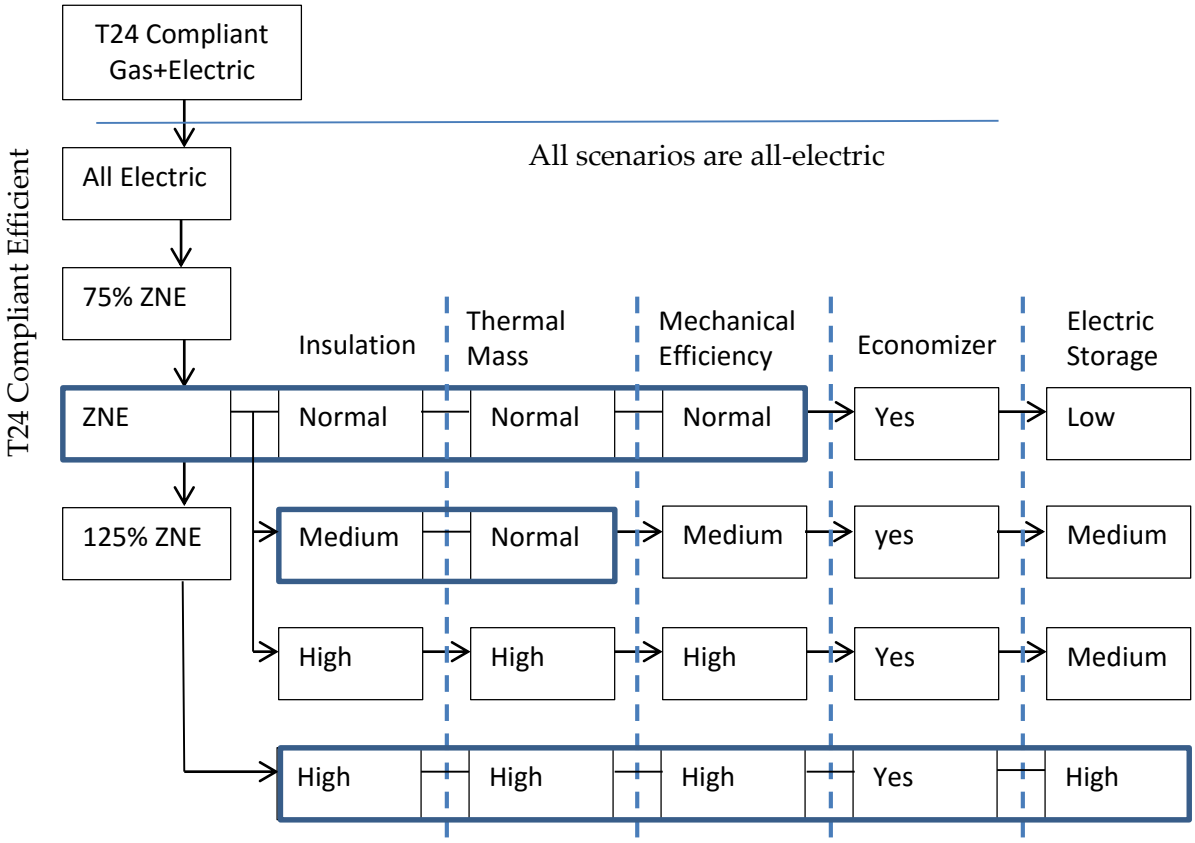
4.4.8 Onsite electric storage

Onsite electricity storage is defined in EnergyPlus with an energy capacity, discharge efficiency, charge efficiency, maximum discharge rate and maximum charge rate. The discharge and charge efficiencies were fixed at 80%. The capacity of the onsite electric storage was sized relative the total energy use for the house on the single most energy intensive day of the year. In addition to the baseline, which had no onsite electric storage, three different capacities were modeled with 75%, 100% and 125% of the annual maximum daily electricity use for the building.

4.5 Results and Discussion

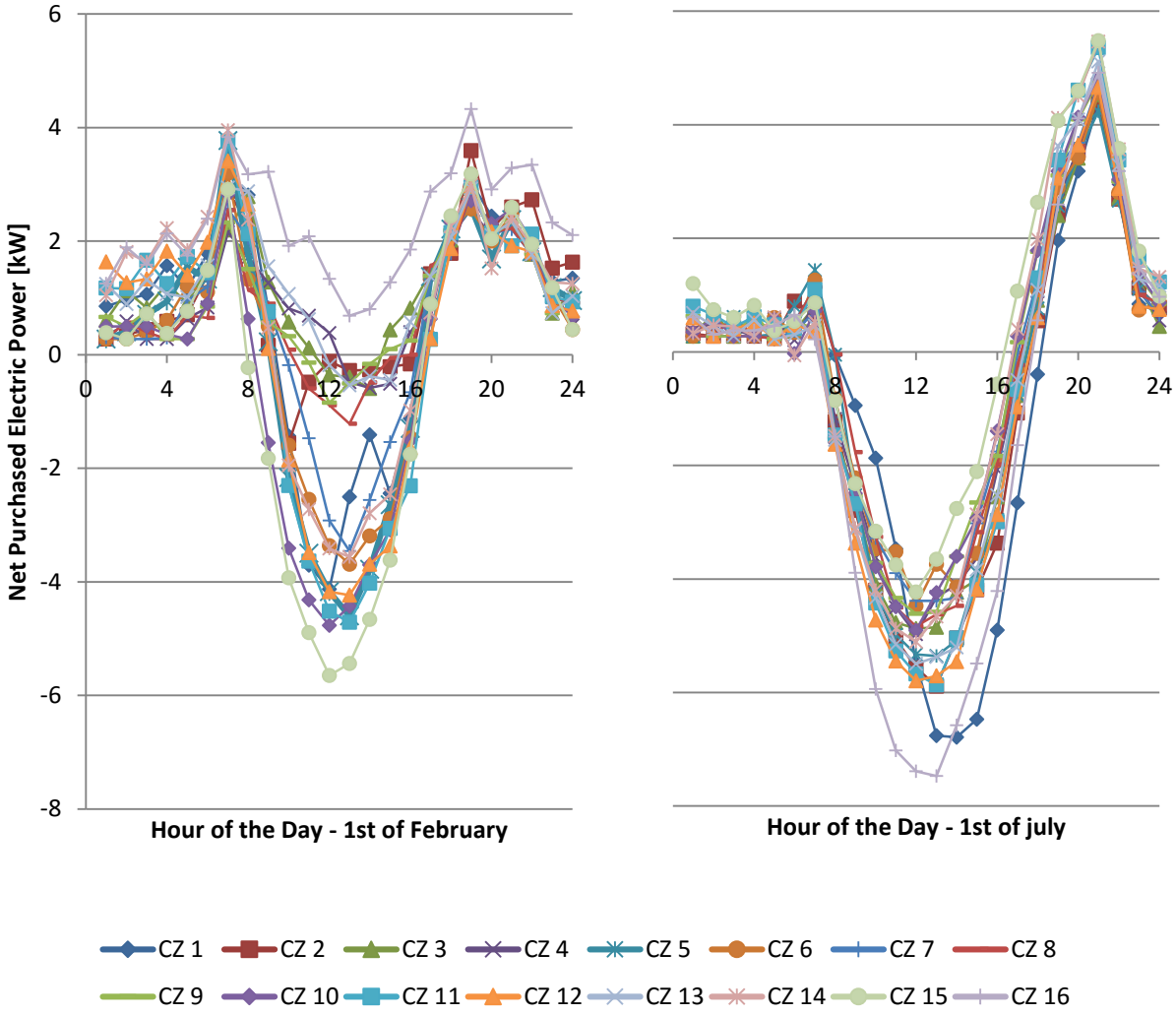
A full parametric analysis for all of the variations considered would result in 648 simulations per climate zone. Rather than analyze the results for more than 10,000 separate runs, a subset of simulations was chosen for assessment, presentation and discussion as a part of this report. The simulation scenarios chosen represent a range of options between the baseline Title 24 compliant gas and electric home, and a very high efficiency ZNE home that incorporates all of the efficiency measures considered. **Error! Not a valid bookmark self-reference.** maps the incremental progression from the baseline case to the high efficiency case.

Figure 31 - The range of different model scenarios considered



The arrows indicate the direction of progression towards higher levels of efficiency. The blue boxes indicate measures that are applied concurrently. The map in Figure 31 results in 17 unique simulations, which were compared and analyzed for this study. The key metric for comparison of each scenario is the resultant net-load profile for the home at different times of the year. For clarity, the net load profile for each scenario considered is presented for two days in the year – February 1st and July 1st. These two days are sufficient to discuss how the major trends shift through the year.

Figure 32 – The all-electric ZNE home in each of California's climate zones



The load profiles of the all-electric ZNE home in each of California's climate zones are shown in Figure 32. The largest variations occur in the winter. In areas with colder winters, such as the Tahoe area (Climate Zone 16) the use of an air source electric heat pump for heating is impractical because the ambient air is simply too cold resulting in poor efficiency. This can be seen in the lack of surplus power generation in such areas during the winter. In the summer all 16 climate zones result in similar load profiles for the all-electric ZNE home. The Sacramento area (Climate Zone 12) will be used for the rest of the analysis as it experiences a wide diversity of conditions throughout the year compared to other milder climate zones.

Figure 33 – Net load profile for 2013-T24 compliant home in CA CZ 12 with different levels of onsite solar electricity generation

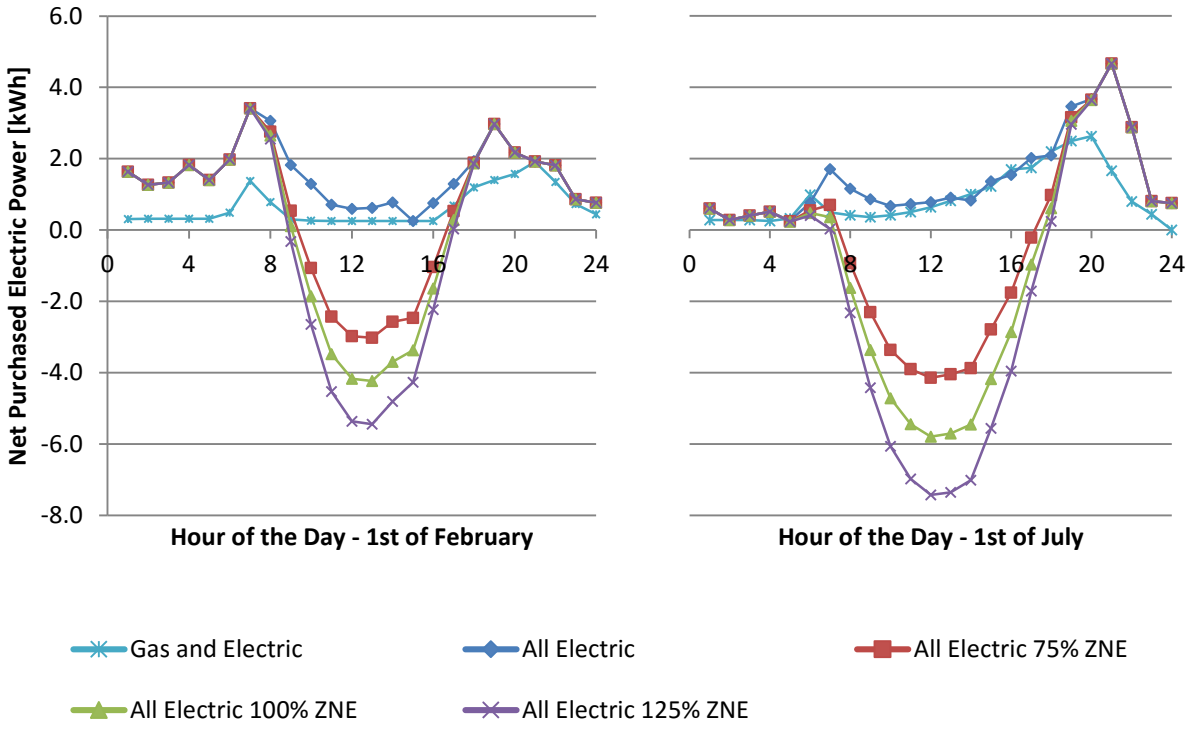


Figure 33 compares the net load profile for the 2013 T24 compliant gas-electric home in CA CZ 12 to that of a similar all electric home, and an all-electric home with different amounts of onsite solar generation. The peak in the net load can be seen to occur at roughly 8:00 pm. The late peak is due to assumptions that were made in the generation of the load profiles. It was assumed that occupants returned to the home each day around 6:00 pm. Variations in the occupant behavior, such as the presence of an occupant who stays home during the day either to work or to care for children would result in a peak in the load profile much earlier in the day.

The baseline case has the flattest net load profile, and the smallest peak demand. The transition to all electric equipment increases the daily variation in load and substantially increases the magnitude of peaks. This is especially true in the winter due to the added electric load from the electric heat pump.

The addition of onsite generation increases daily variation in net-load and oversizing solar capacity makes the variation more dramatic. Notably, for both the summer and winter, peak electricity demand occurs outside the window available for onsite electric generation from solar. As a result, the net-load profile swings sharply from consumption to generation and back to consumption. In the summer, the small morning peak in electric demand tends to be balanced by solar generation, but in the winter the morning peak occurs before solar generation is available.

Figure 34 – Low level improvements to a ZNE home

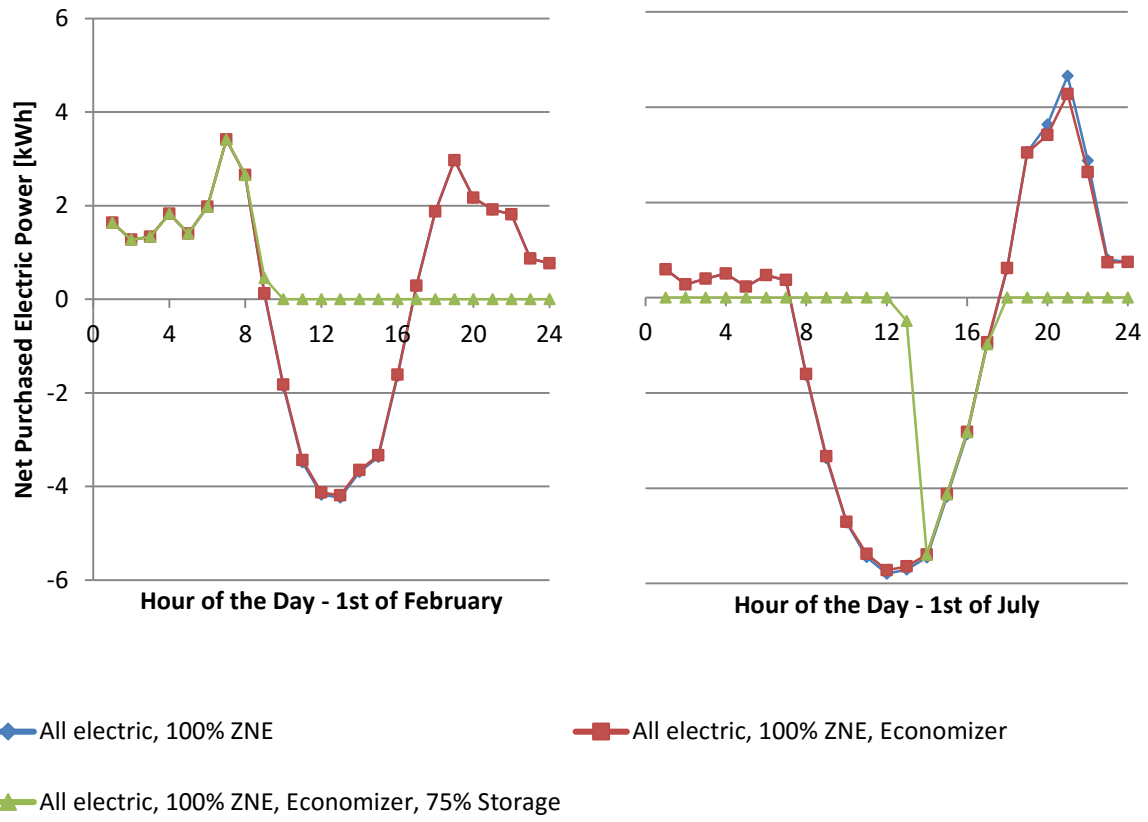
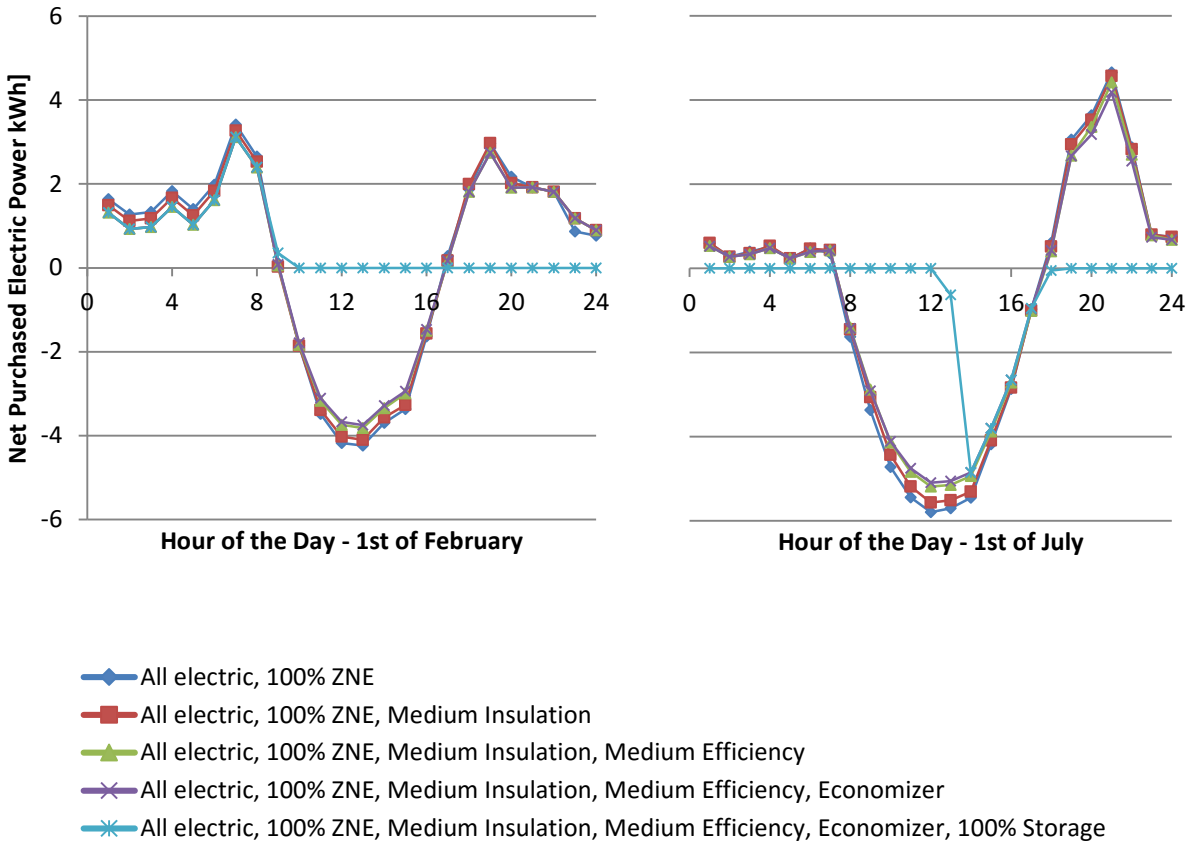


Figure 34 compares the all-electric ZNE scenario to the net-load profile results from the simulations with two efficiency options: addition of nighttime ventilation pre-cooling, and addition of simple electric storage. The electric storage scheme modeled here absorbs as much on-site electric generation as possible and is used as the first priority to cover household loads instead of the grid. It is not controlled for time of use; instead it absorbs as much as is generated and outputs as much as is demanded, within the limits of the energy storage capacity.

The addition of nighttime ventilation pre-cooling reduces the cooling energy use. The largest reduction in cooling energy use takes place in the evening when the outdoor air is cooler than the return air. The cooling load is reduced until around noon due to nighttime ventilation pre-cooling from earlier in the morning. However, despite these improvements, the overall net-load profile is not changed substantially.

Onsite electric storage improves the load profile in the winter by absorbing energy produced by onsite solar during the day, then returning energy to cover household electric loads in the evening. A similar effect is seen in the summer, except in this case the onsite electric storage runs out of capacity before the end of the solar generation period. When the charge capacity is reached the surplus electricity is diverted to the grid. This results in a very sudden spike in the net-load profile.

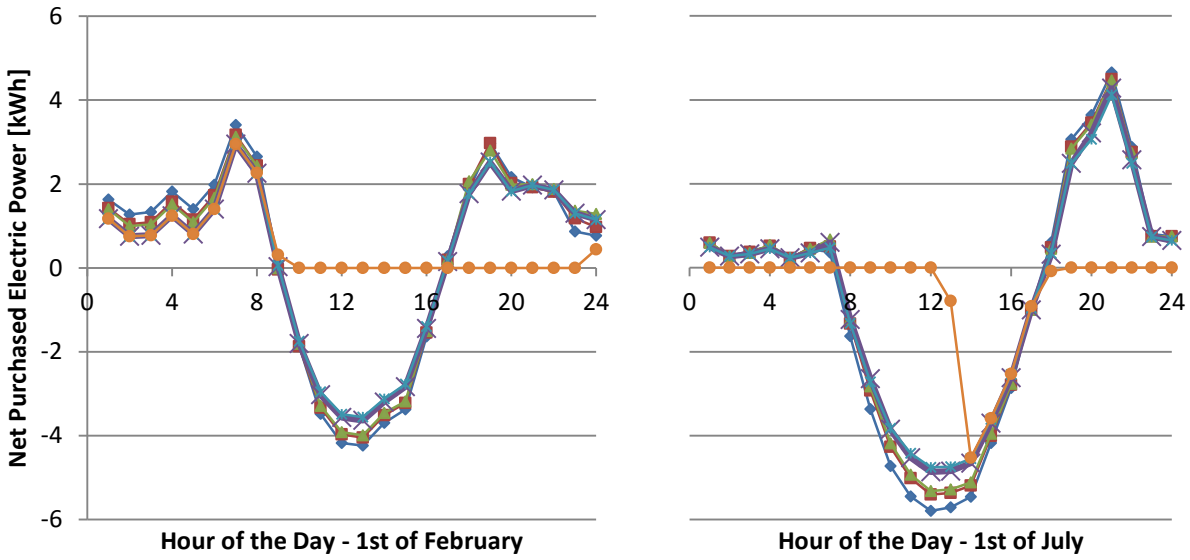
Figure 35 – Mid level improvements to a ZNE home



Net-load profile results from simulations with the mid-level energy efficient improvements are plotted in Figure 35. These mid-level efficiency improvements added R20 wall insulation, then improved equipment efficiency, and finally added a whole house fan for nighttime ventilation pre-cooling.

Increasing the insulation and mechanical efficiency of the HVAC equipment reduces the magnitude of the load profile but does not do much to change its shape. The amount of electricity output to the grid during the day is reduced because onsite solar generation is sized individually for each scenario to achieve 100% ZNE over the course of the year. The more efficient homes have smaller solar systems and thus output less during the day. This result might come as a surprise, since efficiency measures should tend to consume less of the electricity generated from solar.

Figure 36 - High level improvements to a ZNE home.



All electric, 100% ZNE

All electric, 100% ZNE, High Insulation

All electric, 100% ZNE, High Insulation, High Thermal Mass

All electric, 100% ZNE, High Insulation, High Thermal Mass, High Mechanical Efficiency

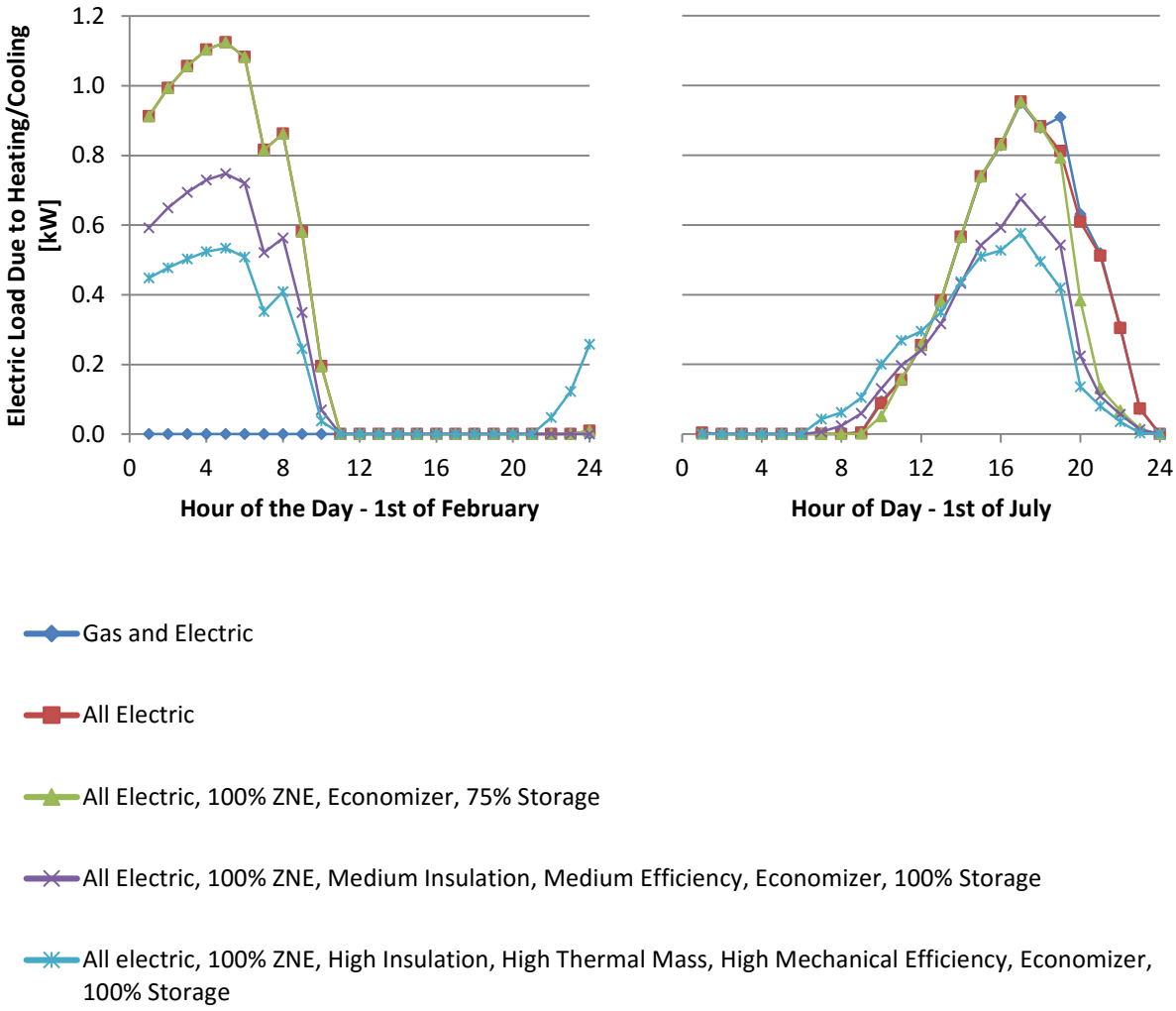
All electric, 100% ZNE, High Insulation, High Thermal Mass, High Mechanical Efficiency, Economizer

All electric, 100% ZNE, High Insulation, High Thermal Mass, High Mechanical Efficiency, Economizer, 100% Storage

The results from simulations with the high-level energy efficient improvements are shown in Figure 36 and compared to the all-electric ZNE scenario. The high-performance energy efficiency improvements have similar effects on the net-load profile as the mid-level improvements, though the magnitude of impact is somewhat larger. Onsite electric storage absorbs the surplus power from solar generation and redistributes it to satisfy the electric demand when the solar power generation is not adequate to meet the building demand. However, when the electric storage reaches capacity or when storage is depleted an abrupt switch to the grid causes sudden changes in the load profile.

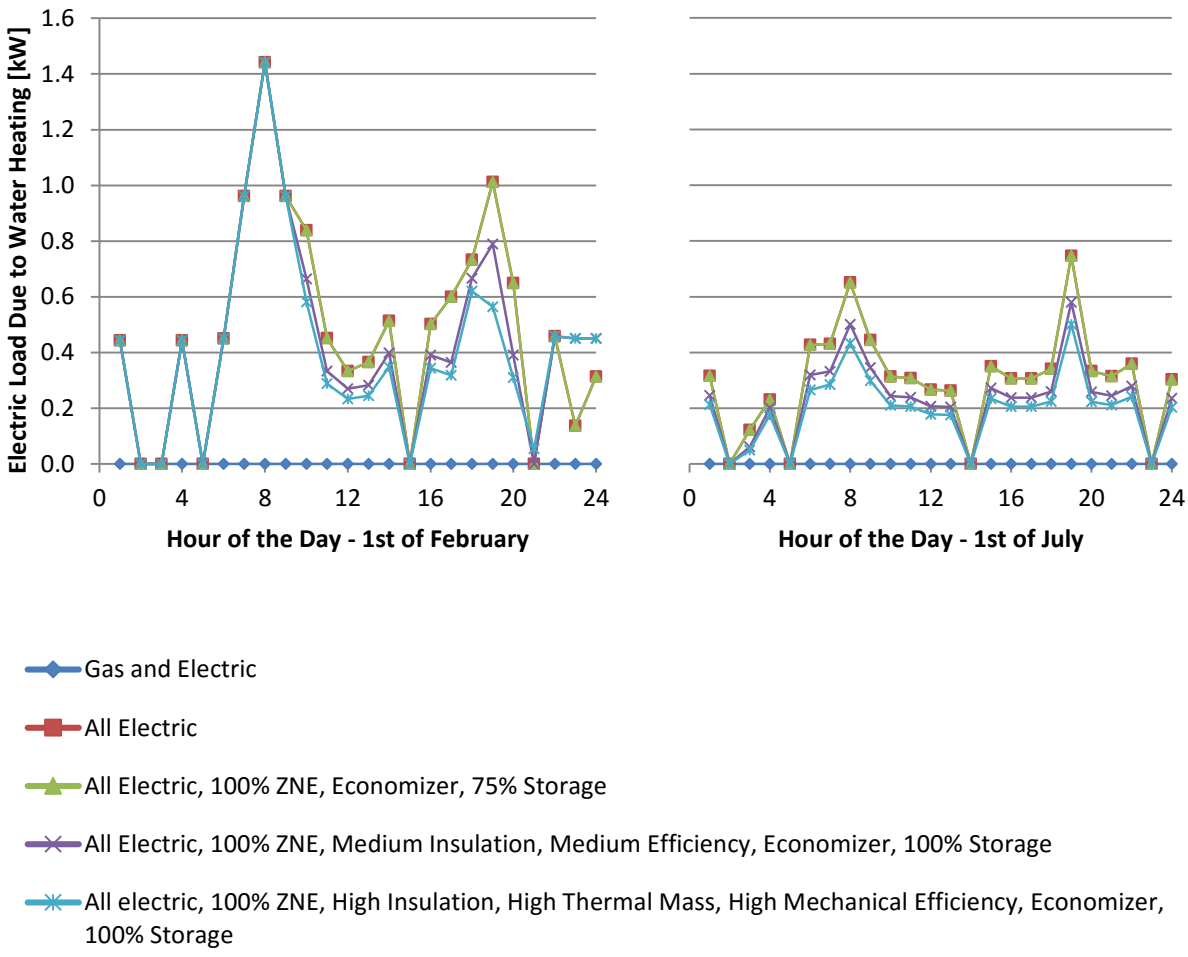
The electric loads due to heating and cooling are broken out in Figure 37 and the water heating load is shown in Figure 38. The loads plotted in Figure 37 and Figure 38 represent the demand and do not account for the power source, be it the electric grid, onsite solar generation or onsite electric storage.

Figure 37 – Electric load due to heating and cooling



An increase in mechanical efficiency for equipment and an increase in thermal mass and insulation for the all-electric ZNE home significantly reduce energy use for heating and cooling. Annually, the high efficiency scenario uses 64% less energy for heating, and 48% less energy for cooling. The peak electricity requirement for heating is reduced by 55% and the peak electricity demand for cooling is reduced by 41%. However, *these measures have relatively little effect on the shape and timing of the net-load profile*. The peak electricity demand for cooling occurs late in the day as solar resources are waning. The peak in electricity demand for heating occurs overnight and in the morning before a substantial amount of solar is available. The economizer reduces load in the late evening when the ambient temperature drops below the indoor temperature – at this point there is an abrupt decrease in electricity used for cooling.

Figure 38 – Electric load due to water heating



Energy use for heat pump water heating accounts for 24-26%- of the annual electricity consumption. In the daily load profile, heat pump water heating is nearly as important as electricity use for heating and cooling. For days in the shoulder season when there are no heating and cooling loads, electricity use for heat pump water heating can plays a more dominant role in the net-load profile. Since it is projected that shoulder season days will be the most challenging for grid management, the energy use for heat pump water heating may play an important role. Unfortunately, since energy use for heat pump water heating is most significant in the morning and evening, these loads tend to aggravate the change between generation and consumption in the residential net-load profile.

Electricity use for water heating is larger in the winter because the efficiency of the heat pump water heater is dependent on the temperature of the outside air that is used as the heat source. In real world scenarios water heating loads can also be larger in the winter if inlet water temperature changes seasonally. Energy use for heat pump water heating is reduced by improved mechanical efficiency, but otherwise energy use for water heating is mostly unaffected by energy efficient improvements in the home.

Figure 39 - Stacked load profile of the all-electric home with each level of efficiency improvements - winter

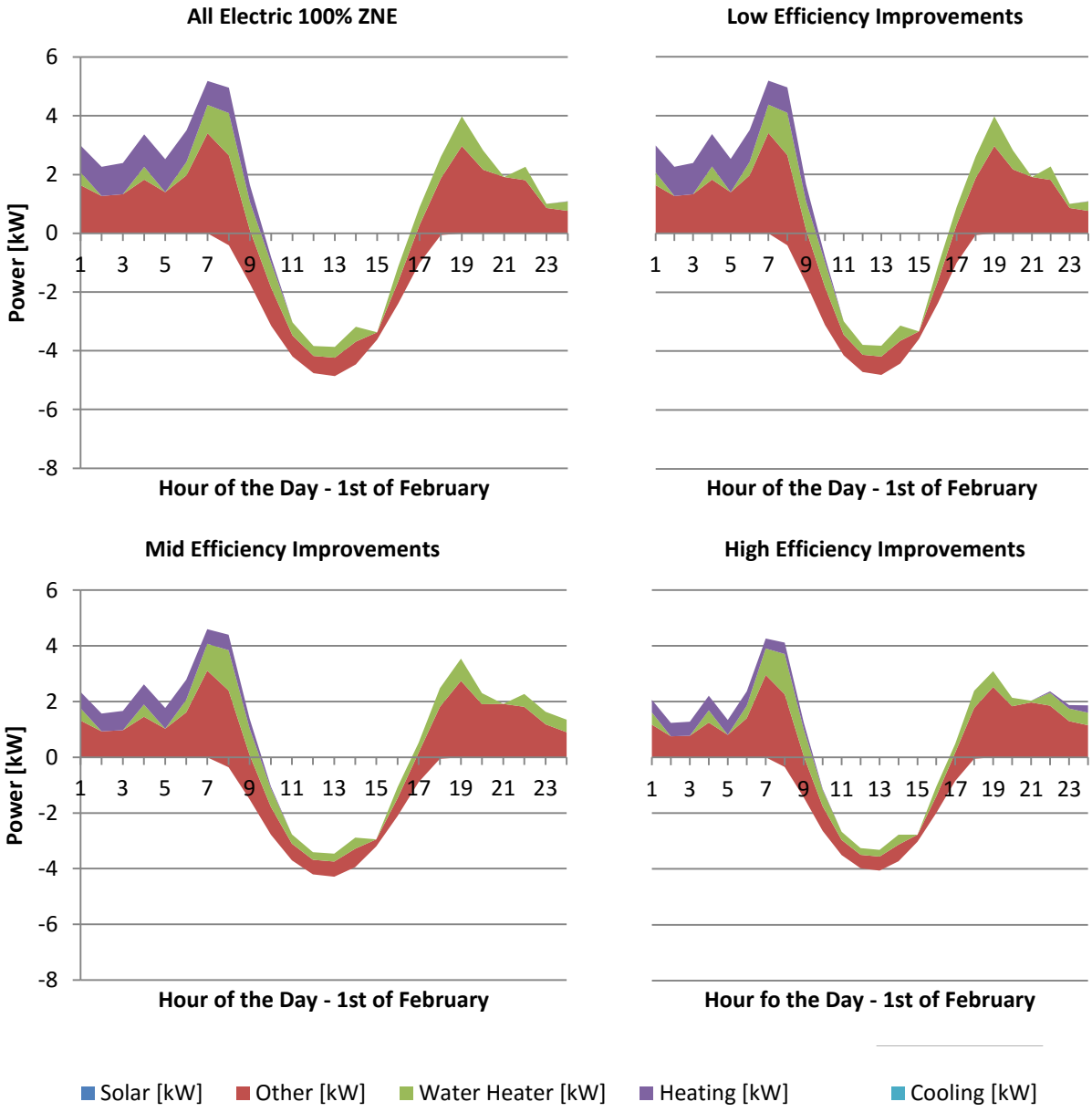


Figure 39 plots stacked net-load profiles to compare the impact of each level of efficiency improvement for the home in winter. Figure 40 plots stacked net-load profiles to compare the impact of each level of efficiency improvement for the home in summer. Area above the x-axis represents power purchased from the grid and area below the x-axis represents loads that are satisfied by the onsite solar generation. The hatched area indicates the net amount of solar generation that is available to either charge onsite electric storage or return to the grid.

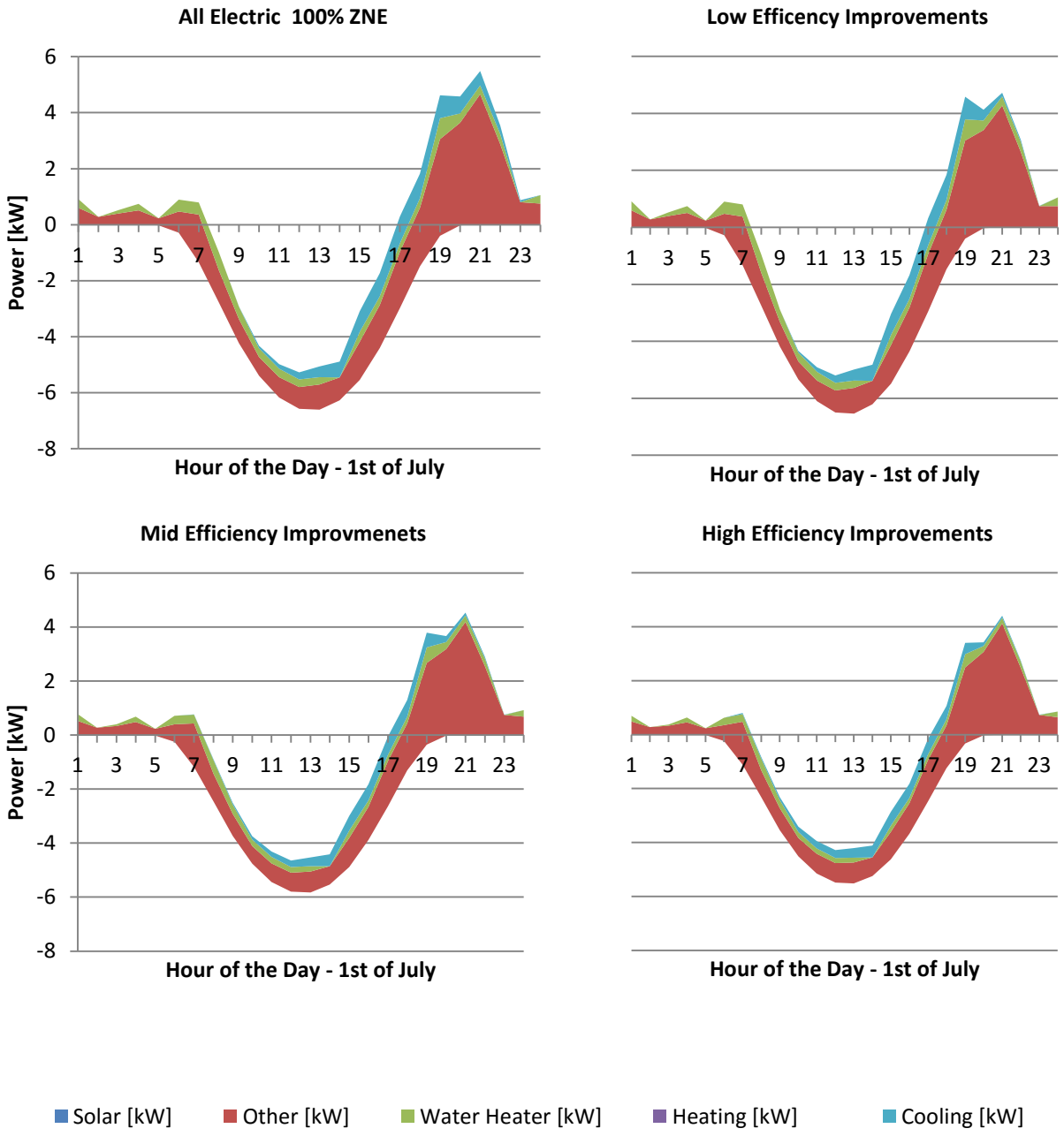
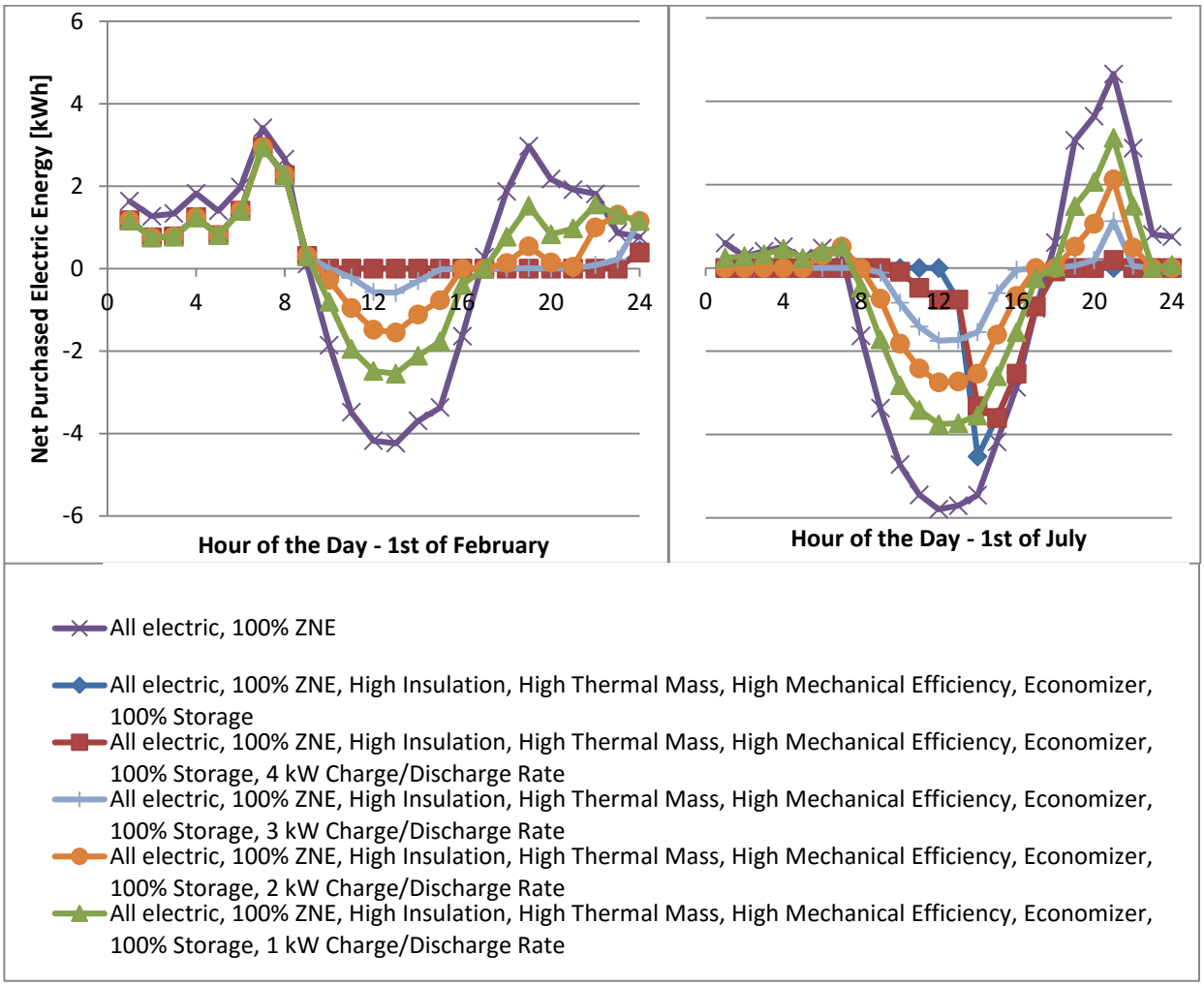


Figure 40 - Stacked load profile of the all-electric home with each level of efficiency improvement - summer

The most significant observation from these comparisons is that HVAC efficiency measures have a limited role in shaping the net-load curve. HVAC equipment makes up a small amount of the load during the peaks in the net-load profile, so improving HVAC efficiency doesn't do much to change the timing or magnitude of the peak demand. The most significant impact from these efficiency measures is that they allow for a smaller photovoltaic system, which reduces the magnitude of generation in the middle of day, and thus flattens the net-load profile somewhat.

Figure 41 Limited electric storage charge and discharge rates



HVAC and hot water efficiency measures have limited potential to shape the net-load profile for ZNE homes. Since the majority of other loads are coincident with occupancy, shifting the residential net-load profile is a challenging prospect. Of the measures studied here, battery storage has the greatest potential to shift the net-load profile. However, if battery storage is not sized and controlled properly it can result in undesirable spikes in the net-load that could worsen the grid management challenges that it intends to resolve. In order to demonstrate the importance of appropriate storage sizing and control, simulations were conducted to limit the rate of charge and discharge from a battery system; Figure 41 Limited electric storage charge and discharge rates documents the resulting net-load profile for five different battery storage scenarios in comparison to the all-electric ZNE case with no storage.

The scenarios presented in Figure 41 Limited electric storage charge and discharge ratesall have the same energy storage capacity, but the charge and discharge rate is limited differently in each. If the charge and discharge rate is limited too far the electric storage becomes ineffective at absorbing and redistributing the power from the onsite solar generation. If the rate is not limited enough then the storage often reaches capacity which results in abrupt swings for the

load profile. For the scenarios compared in **Error! Reference source not found.**3 kW charge and ischarge limit flattens the load profile more than any other measure investigated.

4.6 Conclusions

The parameters that were found to have the biggest impact on the load profile were the energy source (gas or electric) of equipment and appliances, the level of onsite solar generation and the capacity and operation strategy of onsite electric storage. While energy efficient improvements to the ZNE home were found to reduce overall power consumption they had little effect on the shape of the load profile.

For the owner of a solar powered home, electric appliances and equipment can be more cost effective than gas appliances and equipment. The operation of gas consuming appliances and equipment coincides with the peaks in residential power consumption. Replacing gas appliances with their electric counterparts results in an increase in the peak electric load. This increase is significant because according to the RASS appliances such as the water heater, clothes dryer and cooking range account for 40% of the annual electricity use in an all-electric home.

Peaks in the residential electric load on the power grid are largely unaffected by the addition of onsite solar electricity generation because there is typically little solar energy available during peak hours. Instead, a peak in electricity flowing back to the grid occurs in the afternoon when demand is low but the availability of solar energy is high. This fact may be especially important for the design of local electric distribution for zero net energy neighborhoods.

Electricity generation from solar energy is often perceived as a means to improve the efficiency and reduce the cost of the generation, transmission and distribution infrastructure. However, results from this study show that the benefits of solar energy may not be fully realized unless it is implemented alongside storage and or other demand management practices that can shape the daily electric load distribution.

The simplest way to implement onsite electric storage is to configure it to absorb as much surplus power as possible until its charge capacity is reached and then use that stored energy to power the home before any electricity is purchased from the grid. This control strategy has a negative impact on the grid because it introduces large discontinuities in the load profile. When the storage reaches capacity but surplus power is still available the result is a large and sudden surge of electricity flowing back to the grid. Similarly, when the stored energy is exhausted and there is still demand for electricity the result is a large spike in electricity being drawn from the grid.

The simulation results show that onsite electric storage can be extremely effective in smoothing out the load profile if its control strategy is altered to serve this purpose. By simply setting a fixed limit to the charge and discharge rate, the onsite electric storage can be prevented from reaching full capacity or being fully deplete as often and when these events do occur the transition is less drastic. Of key importance: 46 kWh of storage with an appropriate designed

charge discharge management system could smooth the net load profile for a ZNE home such that it has smaller variation than current 2013 T24 compliant gas-electric homes. This simple strategy could potentially be improved by dynamically controlling the charge and discharge rate and should be the topic of future study.

Onsite electric storage is not a common measure, and in the current cost and utility rate paradigm it is not a cost effective option for homeowners. However, if the net-load profile from ZNE homes is a concern it is clear that battery storage has the greatest potential for shaping the load profile.

The current standard method used by California utilities to charge single family homes for electricity consumption is a tiered rate based on monthly consumption of kWh. As a result, the largest return on investments is achieved by reducing the total monthly kWh of electricity consumed by a home without regard for the profile of the load placed on the grid. Many utilities offer time of use (TOU) rates as an optional alternative billing method. By increasing the rate during hours of peak demand and reducing the rate when demand is low homeowners are incentivized to change their load profile to take advantage of lower rates.

The question is whether or not it is more effective to deploy grid scale storage, or residential scale storage. Time of use rates and interconnection charges could be structured in such a way that encourages deployment of storage in ZNE homes, but it may be more cost effective to allow for unconstrained residential net-load profiles and make necessary adjustments on the grid with centralized storage. There is a similar debate about whether or not central solar generation is a more resource effective approach to broad integration of renewables than is distributed solar generation on individual properties. We recommend that California pursue a diversity of tactics to manage the grid stability concerns related to broad integration of solar and other intermittent renewable resources. To some extent, this should include on site storage, or other active load shifting technologies.

Utilities have to justify how much they charge based on their operating costs; therefore, a reduction in operating costs results in a reduction in profit. There is currently no substantial business motivation for utilities to invest in strategies that help to reduce infrastructure for generation, and distribution of electricity. Renewables such as distributed solar power generation on ZNE homes throughout California offer an opportunity to reduce the public investment in central generation and power transmission, but that opportunity relies on the ability to manage the generation, storage and distribution of electricity from solar energy.

Based on the simulation results, as California moves towards ZNE we believe that the State, and utilities should advance efforts such as rebate programs and public interest research that will allow homeowners to shape their load profile in a way that is beneficial to the management of an electric grid with a large fraction of renewables. We also recommend that policy and regulatory measures should develop business incentives for utilities to reduce generation and distribution infrastructure costs in the same way that decoupling has encouraged utilities to invest in efficiency.

GLOSSARY

Term	Definition
PCB	Printed circuit board.
KNN	K-nearest neighbor. Classification (generalization) using an instance-based classifier can be a simple matter of locating the nearest neighbor in instance space and labeling the unknown instance with the same class label as that of the located (known) neighbor. This approach is often referred to as a nearest neighbor classifier. The downside of this simple approach is the lack of robustness that characterizes the resulting classifiers. The high degree of local sensitivity makes nearest neighbor classifiers highly susceptible to noise in the training data.
SPI	Serial peripheral interface is a synchronous serial data protocol used by microcontrollers for communicating with one or more peripheral devices quickly over short distances.
APF	Active power filter is power converter that is typically connected in parallel to one or more nonlinear loads and it cancels the harmonic and reactive components from the loads so that the power grid is free of harmonic and reactive components.
OCC	One-Cycle Control is a nonlinear pulse width modulation method that provides universal control of power converters to realize high fiderity audio power amplification, power factor correction, active power filtering, var compensator, grid-tied inverter, off grid inverter, bidirectional converter, four-quadrant converter, etc. The crown features of this method include simplicity, speed, and stability.
GTI	Grid tied inverter
ZNE	Zero net energy
APFC	Active power factor correction
IC	Integrated circuit
BAUD	Data transfer rate in bits per second
EPIC	Electric Program Investment Charge
Smart Grid	Smart Grid is the thoughtful integration of intelligent technologies and innovative services that produce a more efficient, sustainable, economic, and secure electrical supply for California communities.

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