New Residential Thermostat for Transactive Systems

by

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B.Sc., Building Science, Rensselaer Polytechnic Institute, 1987

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ABSTRACT

This thesis presents a residential thermostat that enables accurate aggregate load control systems for electricity demand response. The thermostat features a control strategy that can be modeled as a linear time-invariant system for short-term demand response signals from the utility. This control design gives rise to linear time-invariant models of aggregate load control and demand response, which is expected to facilitate the design of more accurate load-based regulation services for electricity interconnections and enable integration of more highly variable renewable electricity generation resources. A key feature of the new thermostat design is the elimination of aggregate short-term load control error observed with existing real-time pricing thermostats as they respond to price signals.

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List of Abbreviations and Symbols

Abbreviations

ACE	Area control error
AEP	American Electric Power [Company]
AGC	Automatic generation control
BA	Balancing authority
BPA	Bonneville Power Administration
CPS	Control performance standard
CPP	Critical peak price
DSM	Demand side management
ED	Economic dispatch
ELCAP	End-use load consumer assessment program
FERC	Federal Energy Regulatory Commission
GENCO	Generation company
HVAC	Heating ventilating and air-conditioning
ISO	Independent system operator
LMP	Locational marginal price
LOLP	Loss of load probability
LSE	Load serving entity
LTI	Linear time-invariant

NEEA	Northwest Energy Efficiency Alliance
NERC	North American Electricity Reliability Corporation
NIST	National Institute of Standards and Technology
PNWSG	Pacific Northwest Smart Grid [demonstration project]
RBSA	Residential Building Stock Assessment
RTO	Regional transmission operator
RTP	Real-time price
SCADA	Supervisory control and data acquisition [system]
TEC	Time-error correction
TOU	Time-of-use [price]
TRANSCO	Transmission company
UC	Unit commitment
UFLS	Under-frequency load shedding
US	United States
UVLS	Under-voltage load shedding

Symbols

a	The second-order term of the house transfer function.	Btu.h/°F
A_H	The total area of horizontal glazing surfaces.	ft^2
A_n	The area of the nth glazing surface.	ft^2
A_V	The total area of vertical glazing surfaces.	ft^2
b	The first-order term of the house transfer function.	Btu/°F
c	The zeroth-order term of the house transfer function.	Btu/°F.h
C_A	The heat capacity of the air volume in the house.	Btu/°F
C_M	The heat capacity of the mass of the house.	Btu/°F

d	The magnitude of the constant heat term of the house transfer function.	Btu/h
D	The thermostat deadband.	°F
E	The indoor air temperature control error.	°F
f	The magnitude of the heat unit-step term of the house transfer function.	Btu/h
I_D	The diffuse global irradiance.	W/m^2
I_N	The direct normal irradiance.	W/m^2
k	The consumer's comfort setting	(p.u.)
K	The comfort control gain	\$/°F
M	The heating/cooling system mode (-1 = cooling, 0 = off, 1 = heating, 2 = auxiliary).	(p.u.)
N_D	The number of days in a simulation.	
N_O	The number of occupants in a house.	
N_T	The number of temperature samples taken.	
p	The pole associated with the indoor air temperature of the house.	/h
P	The energy price signal.	\$/MWh
q	The pole associated with the mass temperature of the house.	/h
Q	The total heat gain (loss) to the air in a house.	Btu/h
Q_A	The heat gain (loss) to the indoor air in a house.	Btu/h
Q_C	The primary heat-pump cooling capacity.	Btu/h
Q_E	The heat gain from gas and electric end-use systems in the house.	Btu/h
Q_I	The internal heat gains to the air in a house.	Btu/h
Q_S	The solar heat gains to the air in a house.	Btu/h
Q_H	The primary heat-pump heating capacity.	Btu/h
Q_M	The heat gain (loss) to the mass of the house.	Btu/h

Q_O	The heat gain from occupants in the house.	Btu/h
Q_V	The heat gain (loss) from ventilation air changes through the house.	Btu/h
Q_X	The auxiliary heating capacity.	Btu/h
s	The complex Laplace variable.	/h
t	The real time variable.	h
T	The indoor air temperature relative to the equilibrium temperature.	°F
$\dot{T}$	The first derivative of T.	°F/h
$\ddot{T}$	The second derivative of T.	°F/h^2
T_0	The initial indoor air temperature relative to the outdoor air temperature.	°F
$\dot{T}_0$	The initial rate of change of the indoor air temperature relative to the outdoor air temperature.	°F/h
T_A	The measured indoor air temperature in a house.	°F
$\dot{T}_A$	The measured indoor air temperature change in a house.	°F/h
T_D	The desired indoor air temperature in a house.	°F
T_M	The mass temperature of the house.	°F
$\dot{T}_M$	The rate of change of the mass temperature of the house.	°F/h
t_{min}	The minimum system runtime.	h
t_{max}	The maximum system runtime before auxiliary heating is engaged.	h
T_O	The outdoor air temperature.	°F
T_p	The initial air temperature response of the house.	°F
T_q	The initial mass temperature response of the house.	°F
t_s	The temperature sampling or price signaling interval.	h

T_∞	The equilibrium air temperature of the house.	°F
$u(0)$	The unit-step function applied at time $t = 0$.	(p.u.)
U_A	The conductance of the house envelope.	Btu/°F.h
U_M	The interior mass surface conductance.	Btu/°F.h
$\dot{V}$	The ventilation rate of the house.	/h
W	The measured power demand of the house.	kW

Greek Symbols

α_n	The direct beam incidence angle of the nth glazing surface.	deg
ΔT	The thermostat setback temperature offset.	°F
ρ_G	The glazing shading coefficient.	(p.u.)

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I offer very special thanks to my family for their support and patience, especially Norma, Isaac, Forrest, and Nik Chassin and Ann and Jeffry Mallow for always being ready with a helping hand and covering for me while I was away.

Victoria BC, 2014

DEDICATION

To my beloved Norma

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Chapter 1

Introduction

1.1 Motivation

In 2011 the United States Federal Energy Regulatory Commission issued FERC Order 745, which amends its regulations under the Federal Power Act to ensure that demand response resources with the capability to balance supply and demand can participate in organized wholesale energy markets as an alternative to generation resources. The order introduced requirements that a) dispatched demand response resources satisfy a net-benefit test, and b) demand response resources are compensated for the services they provide to the energy market at the locational marginal price (LMP). This approach for compensating demand response resources was intended to "ensure the competitiveness of organized wholesale energy markets and remove barriers to the participation of demand response resources, thus ensuring just and reasonable wholesale rates" [1].

The US Court of Appeal's recent decision to vacate the order calls into question FERC's entire approach to demand response [2]. The court found that FERC does not have jurisdiction in matters regarding demand response even when they affect wholesale markets. The decision does nothing to solve the problem that FERC was trying to address. Furthermore it remains to be seen whether Judge Brown's dissenting view can prevail and FERC will retain its jurisdiction in all matters relating to wholesale energy markets, including demand response.

Regardless, critics of FERC Order 745 have pointed out that demand response is essentially unlike generation because it is exercised as a call option on the spot energy market, the value of which is the LMP minus the strike price. In the case of retail consumers this price is the tariff rate [3]. Others contend that the value of demand response is the marginal forgone retail rate [4]. However it is valued, the question remains whether FERC Order 745 effectively guarantees double compensation for demand response by providing to responsive load both the cost savings from energy not provided by the retailer *and* an LMP payment for not using same increment of energy. Such a signal might lead a firm to halt operations even though the marginal benefit of consuming electricity exceeds the marginal cost at LMP. In his comments to the commission during prosecution of the rule-making process for the order Hogan argued that"the ideal and economically efficient solution regarding demand response compensation is to implement retail real-time pricing at the LMP, thereby eliminating the need for [wholesale] demand response [compensation]."

These arguments are academic if demand response cannot be employed broadly for technical or economic reasons. To resolve the technical questions regarding the large-scale feasibility of near real-time demand response the US Department of Energy funded the Olympic Peninsula [5] and Columbus Ohio [6] demonstration projects. The objective of both projects was to address the open technical questions regarding the so-called "price-to-devices" challenge [7] by demonstrating the *transactive control* approach to integrating small-scale electric equipment with utility electric power distribution system operations as a first step toward integrating distributed generation and demand response into wholesale operations. Transactive control in this context refers to a distributed resource allocation strategy that engages both electricity suppliers and consumers using market-based mechanisms at the retail level for the purpose of enabling demand response by the utilities at the wholesale level [8].

Without mechanisms like transactive control, price-responsive load requires engaging a very large number of very small participants in the unit-commitment and economic dispatch process. The computational complexity of the optimal dispatch problem makes this impractical for anything more than the thousands of larger suppliers already involved. Strategies extant for addressing this challenge generally involve aggregation at the distribution retail level that enables the integration of demand units by proxy of a reduced number of larger representative units. Private entities such as Enernoc have based their business models on this approach. These are used primarily on commercial buildings where the control systems are more amenable to this integration and the number of control points per Watt of resource is lower than it is for residential buildings. Unfortunately, this leaves nearly half the available building load untapped as a demand resource for utilities.

Using markets to solve electricity resource allocation problems at the wholesale bulk system level is well-understood [9]. But transactive control takes the idea to the retail level by solving the resource allocation problem at the distribution level first before integrating it at the wholesale level. These retail markets are designed to find an allocation of distribution capacity, distributed generation and demand response to resolve how much wholesale energy resource is required and determine how much distributed generators should produce and customers can consume in the coming time interval. Transactive control systems use distribution capacity markets to determine the energy price that minimizes the imbalance between supply and demand for electricity for participating equipment during the next operating interval [10]. The system computes a 5-minute retail real-time price (RTP) for energy that reflects the underlying wholesale LMP plus all other distribution costs and scarcity rent arising from distribution constraints. In cases where large amounts of renewable resources are available the real-time price can be less than the LMP. Negative prices are even possible when a surplus of must-run generation is available. The RTP comes under a new tariff presumably designed to be revenue neutral *in the absence* of demand response.

Distributed generation, load shifting, demand curtailment, and load recovery can be all induced by variations in real-time prices. Given these responses transactive control systems can reduce the utility's long-term exposure to price volatility in the wholesale market and the costs of congestion on the distribution system [11]. These can reduce the long-term average cost of energy for consumers who are willing to forgo consumption in the very short-term. Short-term retail prices are discovered using a feeder capacity double auction and these prices can help manage distribution, transmission or bulk generation level constraints. Distributed generation and demand response are dispatched based on consumers' preferences, which they enter into an advanced thermostat that acts as an automated agent bidding for electricity on their behalf. Transactive thermostats both bid for the electricity and modulate consumption in response to the market clearing price. By integrating this response to a price signal that reflects anticipated scarcity, the system closes the loop on energy delivery and improves resource allocation efficiency by ensuring that consumers who value the power most are served prior to those who are willing to forgo it for a short time. At the same time, consumers provide valuable services to the wholesale bulk power system and experience reduced energy costs at times of day when they express preferences for savings over comfort.

1.2 Main Contributions

The success of demand response programs is highly dependent on the human, technical, and economic behaviors that affect the individual devices that participate in them. Historically human behavior has largely been addressed through conservation and efficiency education and marketing programs. So-called “smart grid” technologies have focused primarily on the technical aspects of system-device communication and aggregate load control designs, typically for “one-shot” demand response to meet peak-load reduction objectives. Transactive control has also focused on the economic aspects of engaging devices in the short-term demand response such that some of the benefits accrue to consumers who offer more flexibility and control over when and how much of their device’s capabilities are deployed.

The most significant objection utilities have to demand response is that demand resources are unreliable and unpredictable. None of the approaches extant have addressed the degree to which individual device controls support reliable and predictable aggregate fast-acting demand response. This thesis presents a new control strategy that addresses these concerns and applies it to an important class of load, namely the residential heating, ventilating and cooling (HVAC) equipment, which dominate demand response programs in certain key regions of the United States. In doing so, this thesis offers the following main contributions:

1. A new thermostat design that enables more reliable and predictable aggregate demand response resources and makes them available to utilities for short-duration fast-acting reliability services. This overcomes the concerns that utilities have with using demand response, particularly in resource planning when they have the greatest financial impact and in system operation when they have the greatest technical impact.

2. A comprehensive set of performance metrics for aggregate demand response control using HVAC. This gives utilities the ability to rigorously design, monitor, and optimize the performance of aggregate demand response control systems. Consequently, utilities are able to provide more reliability services based on demand response to bulk system operators and derive economic benefits that can be passed on to the consumers who provide the underlying resources.

3. An economically and technically robust design for residential HVAC equipment controls that supports aggregate demand response. This gives consumers the ability to better control when and to what degree their systems are participating in demand response services provided by the utility to the bulk system operators.

The application of these results to HVAC should be construed to limit their generality for all thermostatic loads or thermal systems in general, particularly those for which electric demand is influenced by price signals.

1.3 Thesis Outline

This thesis is structured as follows. Chapter 2 provides a critical assessment of demand response in bulk electric power systems and reviews current approaches to delivering demand response resources to wholesale power markets. Chapter 3 introduces a new design for HVAC controls that greatly facilitates the aggregation and delivery of demand response resources by load serving entities to bulk power system operators. Chapter 4 examines this new HVAC control approach using classical control theory, with particular attention to the comfort and cost response to various inputs and disturbances commonly experience in residential buildings. Chapter 5 examines the aggregate impacts of using the new thermostat design by comparing the price-response performance of the new thermostat controls to the transactive designs tested in previous field demonstrations. Chapter 6 presents the conclusions and recommends directions for future research. Appendix A presents the tables from Chapters 1-5 in SI units. Appendix B contains the source code used to run the numerical experiments in GridLAB-D. Appendix C contains a glossary of terms of art used in this thesis.

Chapter 2

Demand as a System Resource

This chapter discusses the background of bulk power system operations, the role of demand response in providing energy, capacity, and reliability services, and how the concept of transactive control enables loads to provide these services. Some challenges associated with transactive control were uncovered by two field projects designed and deployed to demonstrate transactive control. These projects are discussed and problems arising from the existing design are examined.

2.1 Bulk Power System Operations

Responsibility for the reliability of electricity interconnections is shared by all the operating entities within each interconnection. In a traditional power system these entities are vertically integrated. A committee process involving all the entities within each power pool establishes the reliability criteria utilities use for planning and operations. The operating entities typically belong to larger regional coordinating councils so that they can coordinate their criteria with neighboring power pools. These regional councils have been organized since 1965 under what is now called the North America Electric Reliability Corporation (NERC), which establishes the recommended

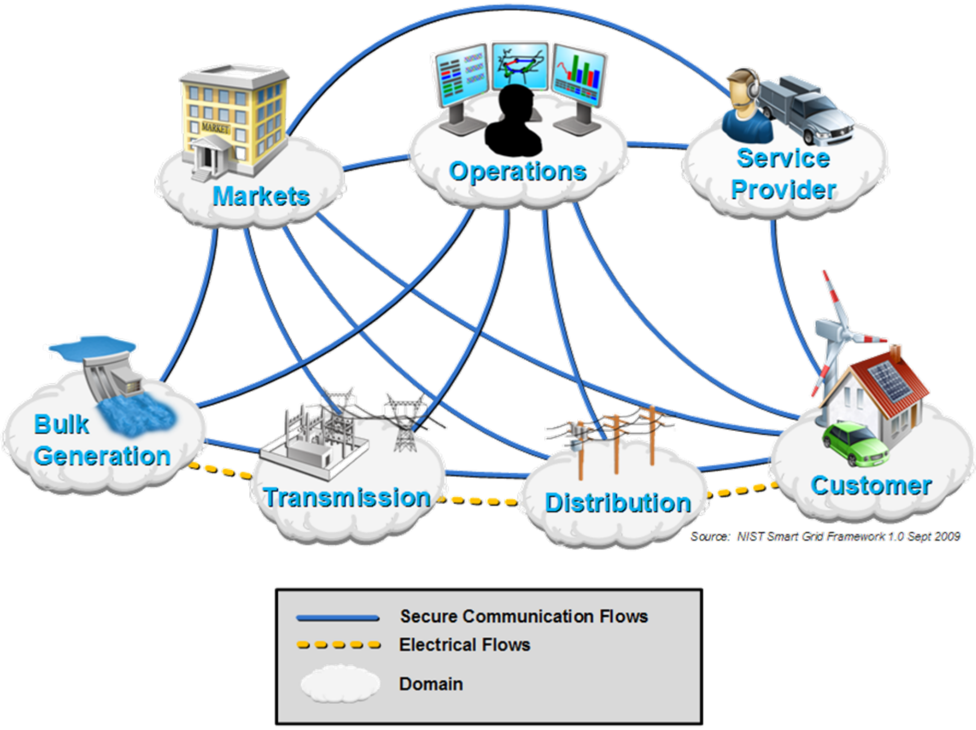

Figure 2.1: Conceptual model of modern electricity operations

standards for system reliability [12]. In a restructured system the responsibility for various aspect of planning and operation are divided among various entities that do not typically fall within the traditional vertically integrated utility operation, as shown in Figure 2.1. The result is a complex network of interacting controls operating over a wide range of temporal and physical scales that requires a very complex information flow to sustain it.

2.1.1 Electric Power Grid Ancillary Services

With the evolution toward market-based operations in recent decades vertically integrated operating entities have been broken up into generation companies (GENCOs), transmission owners (TRANSCOs), load serving entities (LSEs), and energy traders that do not own assets. Collectively these are referred to as the market participants

[13]. The responsibility for ensuring the reliability of a control area is delegated to independent system operators (ISO) or regional transmission operators (RTO). In general market participants have the duty to provide accurate data about their assets and prices as well as follow the dispatch orders of the ISO/RTO. The ISO/RTO has the duty to ensure that each market participant meets the reliability rules and determines the dispatch orders necessary for the electricity supply and demand to match according to NERC's reliability standards. This system is predicated on a successful competitive market in which private decentralized trading and investment design work to allow substantial commercial freedom for buyers, sellers, and various other types of traders [14].

The method used to implement this dispatch model uses a two-stage process referred to as the unbundled or two-settlement approach:

1. Unit-commitment (UC) is a days-ahead process that determines the hourly operating set points of the generation assets based on their bid energy prices and the forecast system load.

2. Economic-dispatch (ED) is an hours-ahead process that determines the real-time generation schedules and procures additional supply to ensure system reliability.

This two-settlement approach can be used for both regulated and unregulated markets and the analysis method is similar for both short-term operations and long-term planning with the only caveat that ISOs must perform the system studies for deregulated markets to determine whether additional generation and transmission may be required.

The timeframes for planning and operations can be separated into the following security functions [15]:

1. Long term planning ($>$ 2 years) determines needed investments in generation and transmission.
2. Resource adequacy (3-6 months) secures generation to serve expected load and sets long-term maintenance schedules.
3. Operations planning (1-2 weeks) coordinates short-term maintenance schedules and long-lead generation.
4. Day-ahead scheduling (12-24 hours) performs a security-constrained UC using energy bids.
5. Real-time commitment and dispatch (5-180 minutes) performs real-time security-based economic balancing of generation and load.
6. Automatic control ($<$ 5 minutes) performs output control of generating resources and actuation of protection system.

For time-intervals shorter than 5 minutes, the reliability of the system is delegated entirely to the generators and load-serving entities according to reliability standards promulgated by NERC and coordinated separately by each interconnection.

2.1.2 Ancillary Services Using Load Resources

Modern bulk electric interconnections are constrained by the physical requirement that electric energy is not stored in any substantial way during system operations. Any mismatch between generation and load will result in a rapid change in frequency over the entire interconnection. These frequency changes can damage equipment and increase electrical losses if left unchecked. Historically utility operations used controllable generation to provide the ancillary balancing services needed to "follow" load to ensure that at every moment supply precisely matches demand and losses. To make electric utility planning and operation economical and manageable the industry divides generation resources into three principal categories: base-load, intermediate load, and peak load [16].

Base-load generation is the bottom portion of the supply stack that essentially runs uninterrupted throughout the year (except during maintenance or unplanned outages). Intermediate generation runs continuously but only seasonally as the diurnal load nadir rises and falls. Peak generation is the supply that must be started and stopped daily to follow the diurnal load variations and meet the annual peak load. Each of these types of generation may also provide regulation and reliability resources to help control frequency and respond to contingencies and emergencies in generation and transmission operations.

For decades load had not been considered part of the overall planning and operations model of electric interconnections except to the extent that its growth sets the conditions for capacity planning. But in recent years increasing attention has been directed to understanding the role that load can play as a resource beyond conservation measures that reduce the need for new conventional generation resources. Load is now seen as a potential resource that avoids using generation resources in inefficient ways and enables the addition of generation resources that exhibit substandard performance characteristics when operating under the conventional load following paradigm [17].

Today the term "demand resource" encompasses a wide range of products, services, and capabilities related to the control and management of load in electric systems. Prior to the advent of "smart grid" technology demand resources were primarily considered for planning purposes, such as demand-side management (DSM) programs, and very limited operational purposes such as *in extremis* under-frequency or under-voltage load shedding programs (UFLS/UVLS). DSM programs are planning programs that focus on energy efficiency and other long-term demand management strategies to reduce load growth so that the need for significant new generation capacity investments can be reduced or deferred. Generally these programs pay for themselves by reducing capital costs for a number of years, possibly indefinitely. DSM programs helped the industry transition from its pre-1970s 7% annual capacity growth to the sub-3% growth prevalent today in modern electricity interconnections.

But DSM programs have a number of long-term limitations that prevent their application to other system planning or operations objectives. First, energy efficiency generally has a diminishing marginal return because every additional dollar invested replaces more efficient load than the last dollar invested. In addition, DSM programs can give utilities a perverse incentive to substitute investments in a few larger, presumably more efficient, base load units with numerous smaller, generally less efficient, intermediate units or even very inefficient “peaker” units. Finally, DSM programs generally do not provide the capabilities and controllability needed to address emerging planning and operations challenges such as generation intermittency, the lack of transmission capacity investments, evolving load characteristics, new ancillary service market designs, and short-term/real-time energy price volatility [18].

On the other end of the spectrum, UFLS and UVLS are strictly operations programs that focus on very short-term load curtailments under severe contingencies. They are used when all or part of the electric interconnection is threatened by a large unexpected loss of generation or system separation that creates a power imbalance which can only be remedied by drastic and immediate reductions in load.

These protective load shedding programs have important limitations because they are pre-programmed actions armed to respond to specific circumstances identified during planning studies. They are not the flexible and graduated responses needed for more general and frequent regulation and balancing operations. Load shedding programs also tend to indiscriminately disconnect loads and do not have the ability to affect only less critical end-uses such as air-conditioners and water-heaters. Some recent trends and developments in more advanced load control address a wider range of short-term operational and economic system needs. These actively controlled loads are called demand response. The focus of current interest is on the benefits and costs, as well as understanding and mitigating the limitations of demand response systems.

Demand Response Resources

Demand response programs have generally been divided into two major categories: incentive-based programs and price-based programs. Both categories recognize that there is an important economic component to developing demand response capabilities in electric systems, but achieve the economic benefits in very different ways. As a general rule, incentive programs are contractual, typically bilateral arrangements between customers and system operators to provide direct load control, interruptible load, or market-based control strategies for emergency reserves and ancillary services. In contrast, price-based programs use utility rate structures and energy prices such as time-of-use rates, critical-peak pricing, or real-time pricing to drive demand to be responsive to system conditions through economic signals as a proxy for direct control signals [19].

The ability of load to provide planning or operations resources is limited by 1) our lack of understanding of the intrinsic nature of the devices and equipment composing the end-use loads and the constraints arising from consumer behavior and expectations; 2) our inability to control those end-use loads in an appropriate and dependable manner, and 3) our inability to validate, verify and meter each rate payer's contributions to system planning and operation.

Load Modeling

The electric utility industry is extremely risk-averse because such a high value is placed on system reliability. As a result new technology is often limited by the ability of planners to model its effect in the planning studies used to establish system operating limits, and by the ability of operators to control those technologies when deployed in real-time. In both cases, the challenge is not only modeling the technology itself, but also more critically simulating how the technology interacts with other resources in the bulk power system. In the case of loads as resources for system planning and operation this modeling issue centers on three fundamental questions: 1) How do electric loads behave at various times of day, week, year? 2) How does end-use composition evolve over these time frames? And 3) how does the control of loads affect these behaviors in shorter time horizons?

Load behavior is determined by both the electro-mechanical properties of the devices and equipment connected to the electric system and by the behavior of the consumers of the services they provide. As a general rule utilities categorize residential loads by end-use, such as cooling, heating, refrigeration, lighting, cooking, plugs, washing, and drying. In commercial buildings other end-uses such as computing, process pumping, conveying, and other services are also considered. Daily, weekly, and seasonal load-shapes are associated with each of these end-uses to provide analysts with an empirical data set from which to estimate load under different conditions. Load shapes have the advantage of capturing in a single data set both the electro-mechanical behavior and the consumer behavior that gives rise to the overall shape of loads [20].

Unfortunately these load shapes have a serious drawback when one attempts to determine the degree to which a load changes in response to short-term signals such as dispatch commands, real-time prices, frequency or voltage fluctuations: load shapes contain no information about the temporal transfer of demand for energy, power and ramping behavior. Devising load models that incorporate these remains an ongoing area of research and tools such as LOADSYN [21], the WECC Composite Load Model [22], and GridLAB-D [23] partly address this problem.

Load composition models were developed to address electromechanical questions that generally do not arise when considering load behavior over hours or more. Each load is composed of electrical subcomponents that have independently changing sub-hourly electro-mechanical characteristics. Induction motors of different types, sizes and control may start and stop, electronic power drives may be used, and the overall mix of static power, current, and impedance may change very quickly in response to dynamic frequency/voltage events, economic or dispatch signals, whether due to the normal internal control behavior or equipment protection subsystems. Although the overall energy consumption on the hourly timescale may be described well using load shape data, the sub-hourly dynamics of power demand may be quite volatile and is often poorly understood. This lack of understanding can present system planners and operators with challenges for which few tools exist, as has been noted in the case of fault-induced delayed voltage recovery [24].

Load diversity is an emerging challenge when external control signals are applied to devices and equipment. Under normal operating conditions loads that cycle on and off are assumed to have high diversity, meaning that the start and stop times are independent of bulk system conditions and thus uncorrelated to each other. The difficulty is that diversity is a property of loads similar to entropy; it is difficult to directly observe but can be influenced by external forces, such as load-shift or load-shed control signals. Because diversity is not a property of individual loads it can only be measured meaningfully relative to a reference state, such as the equilibrium state of a class of loads. Conventional models of loads assume the diversity is maximal, i.e., at equilibrium. But in practice load control strategies reduce diversity, sometimes to a significant degree. In spite of these challenges models that indirectly consider the entropic properties of certain load classes have been developed and applied to load control problems with some success [25] [26] [27]. But a comprehensive and theoretically sound model for diversity continues to elude load modelers and this remains an open area of research.

Human behavior is a critical factor affecting load that must be considered when designing load control programs. Utilities must consider two distinct aspects of human behavior to determine the viability and success of a load control program. The first is customer recruiting and retention and the second is real-time consumer participation[1]. Demand response program marketing is primarily based on economic claims but often includes an environmental component. Customer expectations are set during the recruiting phase when utilities make a cost-benefit case for customers to opt-in to demand response programs. After customer acquiescence, technology is usually deployed in the customers' facilities and consumers are presented with behavioral choices by the technology. The frequency of these choices can range from daily, such as postponing a load of laundry, to seasonal, such as resetting a thermostat. Expecting consumers to make choices more than once a day for any particular end-use is generally regarded as impractical. It is also usually ineffective to ask consumers to make choices less frequently than seasonally [5]. Mitigating consumer fatigue and providing continuous education have also been observed to be factors in ensuring that demand response programs are cost-effective and sustainable [28] [29]. Finally, utilities frequently face fairness and "free-rider" questions when customers sign-up for programs but provide no marginal benefit to the utilities because either they already exhibited the behavior sought, or the utility never calls on them to exhibit the desired behavior [30]. Ultimately the long-term effectiveness of demand response

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[1] The customer pays for electric services but may not be the same person as the consumer who uses the end-use service.

programs and the technologies that supports them hinges on whether the individual and aggregate value outweigh the individual and aggregate impacts. Any disconnect between customers/consumer short-term/long-term value/impacts and they will not remain in the program long enough for the program to pay for itself let alone provide the anticipated system benefits to the utilities and system operators [31].

Until the advent of utility deregulation, demand response programs were the exclusive purview of utilities and regulated accordingly. However, in regions where vertical integration has been overcome, third-party aggregation has become a viable business model for providing demand response from many smaller customers as a single homogeneous capability that is easier for a utility or an ISO to interact with. By using on-site control technology, utility service contracts, and rebate programs aggregators can create both arbitrage and value-added opportunities from which to generate sufficient revenue. In some cases, monopsony/monopoly conditions can emerge as a result of regulatory intervention, technology locked-in, high front-end equipment costs and high back-end system integration costs [32]. A recent additional concern is that demand response aggregation is potentially subject to FERC jurisdiction to the extent that aggregators acquire and deliver resources across FERC jurisdictional boundaries or interact with ISO and RTO entities subject to FERC oversight. Indeed FERC orders affecting how demand response is compensated in energy markets raise the question of whether and how it might intervene regarding demand response compensation in ancillary service markets [1].

Load models ultimately are embodied in the simulation tools utilities use in planning studies and operational analysis. These include forecasting models and even billing systems where baseline load models are part of the service contract. But new load models can take a very long time to be adopted by industry and become commercially available in planning and operations products. For example, the Western Electricity

Coordinating Council (WECC) Load Modeling Task Force began developing a new load model in 2001 but it was not adopted until the WECC Summer 2013 studies. In the interim a flat 20% induction motor load model was used after it became apparent that the standard load model was in part responsible for the discrepancies observed in the August 1996 outage studies [33]. Such delays can significantly reduce the impact and potential benefits of load control technology, and approaches to faster load model validation and adoption are still needed.

Load Control

Demand response as a tool for providing ancillary services relies on the ability to deliver fast-acting control of aggregate loads. The timescales over which loads can respond to dispatch signals and then return to a “ready” state determine the frequency and magnitude of load response as it performs desired ancillary services. The models for such control of loads, as opposed to load response behavior, have yet to be developed. Work to describe the frequency and amplitude response of modern loads and load controls has only recently been undertaken and significant research remains to be done in this area [34].

A fast emerging obstacle to effective deployment of large-scale load control systems is the lack of a comprehensive theory of control for distributed systems. Understanding how we regulate devices and systems in our environment is a prerequisite to managing those devices and systems. That understanding is largely captured in classical control theory, the body of mathematical formalisms that explain how we observe, control and verify key performance characteristics of linear time-invariant (LTI) systems. The challenge today is that although controllability and observability are well-defined for LTI systems through the Kalman rank condition and stability can be studied using the analytic methods of classical control theory, the emergent behavior of interconnected systems has yet to be fully described formally. As a result, *ad hoc* models of robustness, security, and stochastic behavior have been overlayed on existing control theory. Physical constraints are often ignored, information flow is assumed instantaneous, and evolving network topologies are not well treated so that only trivial problems are solved [35].

The paradigm for larger more complex and realistic systems continues to elude system engineers. We have yet to understand complex engineered systems well enough to design and control them to the same level of precision we do for smaller self-contained systems, let alone exploit the new behaviors and possibilities inherent when linking previously independent systems into a more heterogeneous multi-technical complex of systems. In short, we need a new approach to controlling the large interconnected multi-technical complex that is emerging. The new approach must allow systems to adapt and evolve without individual components being redesigned, retested, and redeployed every time relevant parameters change. Ultimately a new paradigm of control is needed for these complex systems.

Validation, Verification and Metering

Using demand response as a resource for planning and operation depends on our ability to ensure that the tools we use for bulk power system control are accurate. Demand response programs must work as designed for all foreseeable events and be robust to unforeseeable conditions. Utilities must be able to monitor the performance and meter the billable usage of demand resources for both operational and business objectives.

Model and simulation validation for very complex models such as the load models currently in use is a daunting challenge in itself. Empirical end-use and load composition data collected by utilities degrades quickly and unpredictably as end-use technologies change, efficiency standards take hold and consumer habits evolve. Although utilities know that consumer assessment surveys are essential to maintaining accurate load models, the typical cost of conducting these surveys has been prohibitive. Many utilities and advocates of automated meter reading technology frequently cite improved consumer behavior data as one of the principal long-term benefits of automatic metering infrastructure. However, these benefits have yet to be documented and demonstrated in practice, particularly as data privacy and security concerns begin to emerge [36].

Tool validation presents additional challenges, particularly when tools become multi-disciplinary and rely on hybrid numerical methods, such as agent-based solvers. These analysis tools are highly realistic over wide ranges of time scale and can incorporate a wide variety of model order reductions. However they rarely have a reference model or baseline data to compare against. As a result confidence in these tools builds more slowly and the rate of adoption of advanced simulations is slower than has historically been true from more conventional power system analysis tools [37].

Control system verification remains an open research area for distributed control systems such as the large-scale demand response systems being designed and tested today. Utilities historically relied on strictly hierarchical direct load control programs that used isolated and simple control structures and were easy to verify. Systems that rely on autonomous responses or price signals are more likely to exhibit random deviations that raise concerns regarding their reliability under extreme events when they may become critical to maintaining system integrity [38].

Monitoring and metering are closely related to the question of verification and present additional challenges. Utilities must monitor resource availability in real-time to ensure that sufficient resources are deployed to provide the required contingency response. So-called “transactive” systems have the notable advantage that they provide resource status and availability data concurrently with the required resource cost data. Moreover when events occur utilities need to determine which resources were actually deployed before compensating customers for their participation. To date most of the advanced demand response systems deployed have largely failed to satisfactorily address either of these issues [39].

2.1.3 Demand Response Aggregation Strategies

One of the most significant obstacles to using demand response to simultaneously displace generation-centric reliability services and mitigating generator market power is the mismatch in the characteristic size, time, and uncertainty of loads relative to generators: there are relatively few easily observed generators and their characteristic response times are relatively slow compared to overall system dynamics. Loads in contrast are far smaller, far more numerous and difficult to observe. But loads are potentially much faster acting than the overall system dynamics [16]. Demand aggregation services can be employed in electric power systems operations to enable energy conservation, peak load reduction and load-based reliability services.

Bulk power system planning, operation and control have generally been designed to consider the characteristics of generators and treated loads as a “noisy” but forecastable boundary condition. Thus load control remains quite difficult to incorporate into bulk system planning and operation. In general the approach to addressing this fundamental mismatch is to devise demand aggregation strategies that collect numerous small and fast-acting devices with high individual uncertainty into fewer larger-but-slower aggregations with reduced uncertainty. Demand aggregation does not require that every electric customer participate in wholesale markets but it does provide a means of more cost-effectively increasing consumer participation in system resource allocation strategies, whether market-based or centrally controlled, and can mitigate price volatility for energy, capacity, or ramping services [40].

From an economic perspective aggregating electricity customers can be viewed as a means of converting consumer surplus to producer surplus by segregating consumers[2] into groups with different willingness to pay. Three general approaches are usually employed to create load aggregates for either operational or economic objectives:

1. Technical aggregation creates technical structures that either directly aggregate consumers, or indirectly enable economic or social aggregation using technical means. Technical aggregation can be accomplished using service aggregators, creating technological lock-in with high barriers to entry or exit, or constructing local retail markets independent of the wholesale energy, capacity, and ancillary service markets.

2. Social aggregation is achieved using various subsidy programs and other social group identification strategies, such as environmental, green, or early-adopter programs.

3. Economic aggregation is achieved using price discrimination methods such as different tariff rates for different customer classes, product differentiation, and product or service bundling strategies.

Technical customer aggregation strategies are less common in the electric utility business than might be expected for such a technology-intensive industry. Only a few types of technical customer aggregation strategies can be readily discerned in modern utilities operations. Most notable are direct and indirect load control, service aggregators, retail markets, and technology lock-in strategies.

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[2] We sometimes must distinguish between *customers* who pay for the energy from *consumers* who use the services that require energy: customers do not always exhibit the demand response behaviors of consumers and consumers do not always exhibit option/strike decisions of customers.

Technical customer aggregation strategies usually support the economic, social and business objectives of utilities and the government oversight that protects the public good portions of their operations. Technical customer aggregation is rarely an objective in itself but for various practical reasons research into technical aggregation is often divorced from these objectives. Indeed some aggregation technologies are criticized for not recognizing these considerations and falling far short of expectations given the costs [41].

Social aggregation is based more on human behavior than economic theory and is consequently less well understood in general. Utilities typically base their social customer aggregates on four types of social differentiators: income class, behavioral cross-subsidies, environmental awareness and early adopters.

Price discrimination is an economic strategy used by sellers to capture additional consumer surplus. Surplus is the economic benefit derived by bringing buyers and sellers together to trade electricity products and services. As long as a consumer's reservation price exceeds the producers' they are both overall better off economically if they complete the trade. The net difference between the consumers' economic welfare with electricity and their welfare without electricity is defined as the consumer surplus. Similarly, the net economic benefit to the electricity producers is the difference in profit derived from producing electricity and that of not producing electricity and is defined as the producer surplus. It is the objective of both consumers and producers to maximize their respective surpluses, which in an efficient market results in the total surplus being maximized as well [42].

However producers recognize that some consumers have a greater willingness to pay for products and services. Consequently producers can devise pricing strategies that divide the consumers in a way that increases their surplus while not increasing the total surplus. This happens when producers simply capture some of the consumers' surplus. The most common of these strategies is to create different rate structures for each customer sector, residential, commercial, industry, municipal, and agricultural. In theory such strategies have been shown to maximize producer surplus only when the demand curve is strictly convex toward the origin $(P, Q) = (0, 0)$. In practice this limitation is often ignored and price discrimination is nearly ubiquitous in the electric utility industry even when there is little or no direct empirical evidence that consumer demand always has the right characteristics. Even though it may seem unfair to consumers that some pay less for the same product or service, price discrimination is regarded as a standard practice justified by the cost recovery needs of a capital intensive industry and by socio-technical trade-offs/cross-subsidies such as differential service quality for low-income consumers and industrial customers. Such practices are widely supported by utility regulators [43].

Volume discounts are another common form of price discrimination that serves to aggregate consumer behavior. In the case of electric utilities, the most common form is the declining block rate, which recognizes that customers with a higher demand also have a more predictable peak demand than smaller customers. The cost of operating electric power systems is driven in large measure by the cost of serving unpredictable peaks so more predictable customers are offered discounted rates for this “good” behavior. In effect these customers are consuming more of a less valuable product because it does not vary as much relative to the total load, and therefore costs less to produce and deliver. An unfortunate side effect of declining block rates is that they can be a disincentive to conservation and many utilities are moving away from such rate structures. Inclining block rates do promote conservation but this approach requires very careful analysis to predict the seasonal peak load variations. When significant numbers of customers come under such a rate, utility revenues can become much more sensitive to weather fluctuations than they already are [44].

Very likely the most well known form of price discrimination employed by utilities is product differentiation, i.e., charging residential customers for energy usage and commercial/industrial customers for power capacity. This form of customer aggregation recognizes that residential and small commercial customer behavior, e.g., individual appliance and equipment purchases, is more closely correlated with energy consumption and large commercial/industrial/agricultural customer behavior, e.g., increasing production capacity, is more closely correlated to peak power demand. Utilities seek to have behavior and bills as strongly correlated as possible and therefore prefer energy rates for residential and small commercial customers and power or demand ratchet rates for large commercial, industrial and agricultural customers [45].

The final form of economic customer aggregation, service bundling, is the most ubiquitous in electricity delivery. The strongly regulated nature of the utility business means that product bundling isn't thought of as a business strategy to increase revenues *per se* as in the telecommunications business. Instead the capital-intensive nature of the business combined with the desire for simple billing means that energy or power rates must include capital costs in a simple "blended" fixed energy price. Service bundling is considered an appropriate net revenue volatility risk mitigation strategy and regulated as such. Most customers pay for only one product composed of several underlying services, such as energy with capacity and reliability bundled, or capacity with energy and reliability bundled. All the underlying services that utilities provide, such as fuel price volatility hedging, capital financing, administration and maintenance are blended into the simple price that each customer pays. There is some discussion of utility business models that unbundle these services to achieve more economically efficient operations by revealing the customers' separate demand elasticities and reservation prices for each service. Utilities would then be able to serve customers with differentiated reliability services, for example. Most likely the technical and regulatory obstacles to this model are why it has not gained much more than academic interest. Perhaps we can expect growing interest in areas where distribution reliability is a significant issue for some customers or technical solutions like microgrids are prevalent. But that has yet to be adequately researched at this point.

Although many of these aggregation methods have existed for decades, recent technological advances have enabled some of them to be revisited and enhanced. In particular early adopter strategies offer utilities the opportunity to test new technologies to meet regulated research program investment obligations and avoid the risk of significant capital investments. Meanwhile operators and customers have to opportunity to learn how to maximize the benefits of new programs before utilities commit to and regulators approve of full-scale deployment.

Price-based strategies provide a balance of economic efficiency and risk mitigation by allowing utilities to transfer some costs more explicitly to customers and reducing the need to engage in more costly price-volatility hedging on their behalf through opaque rate design processes. But regulators remain wary of price-based aggregation strategies until they can be shown to be cost-effective and fair to all customers.

2.1.4 Environmental Impacts of Demand Response

In the previous sections the role of ancillary services, the potential for demand response to provide such services and the strategies available to aggregate demand response services were discussed in detail. We found that 1) ancillary services provide a critical capability for interconnection reliability; 2) demand response has the potential to provide such services; and 3) demand response resource aggregation is necessary to integrate diverse technical capabilities into interconnection planning and operations. In this section we consider the environmental impacts of increased demand response resources in electric systems.

A comprehensive study of smart-grid technology completed for the US Department of Energy in 2010 found that a potential for 12% direct and 6% indirect reduction of electricity sector energy and CO_2 emissions [46]. These included conservation impacts of consumer information feedback system (3% direct impact), deployment of diagnostics in residential and commercial building (3% direct impact), support for additional electric vehicles (3% direct impact) and advanced distribution voltage control (2% direct impact). But the most significant impact was a 5% indirect impact from the support of renewable wind and solar generation.

Variable or intermittent generation is a growing fraction of the resource base for bulk power systems. The variable character of certain renewable resources in particular is thought to undermine the overall reliability of the system insofar as forecasts of wind and solar generation output have greater uncertainty than more conventional fossil, nuclear or hydroelectric generation resources. As a result the expectation is that while variable renewable generation resources do displace the energy production capacity of fossil power plants, they may “consume” a significant fraction of the reserve power and ramping capacity of the plants they are supposed to replace. Consequently renewable resources do not offer as much emissions benefit as expected if one were to assess their impact simply on energy production capacity [47] [48].

It seems intuitive that demand response should be able to mitigate the reserve capacity and ramping impacts of variable generation by reducing the need to build and commit fossil generation to substitute for reserves or ramping required by intermittent renewable generation. But this substitutability is constrained by 1) the nature of variable generation, the role of forecasting, and the impact of resource variability on the emissions and economics of conventional resources; 2) the nature of load variability and how demand response is related to load variability; and 3) the characteristics of end-use demand and the impact of demand response on energy consumption, peak power and ramping rates over the various time horizons that are relevant to the variable generation question.

Taken together these constraints and interactions provide the basis for assessing the economic and environmental impacts of controllable load and demand response resources on various timescales. The economic principle of downward substitutability, i.e., faster ramping ancillary services are more valuable, provides the basis for our assumption that fast-acting demand response resources have greater value than slower generation response resources, all other things being equal. In this case the economic cost of mitigating renewable intermittency at any given timescale using generation resources must be greater than the cost of using demand response with the capability. We may then conclude that when environmental costs are internalized the environmental benefit mitigating renewable intermittency using demand response must be greater than if we used generation resources.

Generation Variability

On the supply side of the reliability equation we find that variability in renewable resources is the most significant contributor to uncertainty in the overall generation production scheduling process. Current renewable generation forecasting tools are based on five technologies—numerical weather prediction, ensemble forecasts, physical models, empirical modeling and benchmarking—that are combined in a 3-step process to produce a forecast. These steps are 1) determine weather conditions, 2) calculate power output, and 3) scale over different time horizons and regional conditions [49]. In general, the root-mean square errors (RMSE) of renewable forecasting methods grow asymptotically as the time horizon is extended with the best models having an RMSE of less than 5% for 1 hour forecasts to over 35% for 3-days forecasts. There is

Table 2.1: Emission reductions relative to no wind generation

	Emissions reduction						
Wind penetration	**CO2**	**N2O**	**CH4**	**CO**	**NOx**	**SOx**	**PM**
10%	12%	9%	12%	10%	13%	8%	11%
20%	21%	11%	17%	15%	22%	17%	22%
30%	28%	10%	21%	19%	29%	24%	32%
40%	33%	4%	23%	20%	34%	30%	40%

Source: Valentino *et al.* (2012)

high variability in the reported performance of different forecasting tools. Because generation resources are dispatched based on these forecasts, the principal component of unscheduled generation deviations is the error in the forecasts of renewable resources [50].

Variable resources do help reduce the need to operate fossil-based power plants and thus reduce emissions to a first order. But this benefit is not on a one-to-one basis because the need to continually adjust fossil plant output can cause second-order increases in emissions due to decreased plant efficiency. For every 3 MW of wind capacity added, only 2 MW of fossil capacity is decommitted. Additional startups reduce the emissions benefits of wind by 2%. Part-load operation reduces the emissions benefits by an additional 0.3% in WECC [51]. In addition at high variable generation levels, some energy may need to be spilled because there are no consumers for it under light load conditions. The effective emissions rate for wind due to these secondary effects relative to a typical interconnection fossil generation mix is about 1-2%/MWh [52].

The overall emissions reductions for wind generation are shown in Table 2.1. Based on the variable resource impacts inequality assumption, we should assume that demand response benefits could not exceed these values.

There are a number of considerations that limit the equivalence between variable generation impacts and controllable load benefits. In particular, the geographic dispersal of variable generation supports diversity, which is a key assumption in estimating their collective reliability impacts. For demand response such assumptions may not hold. In addition, certain regulatory practices such as defining gate closures (the lead time required to procure reserves) may differentially affect how well improvements in forecasting of variable generation reduce reliability impacts relative to changes in load forecasting as more load becomes responsive.

Load Variability

Time-series load data is the foundation of all load analysis. The most commonly available data on load is metered balancing area, substation, feeder, premises, and end-use load data, in decreasing order of availability. Utilities have measured balancing area to feeder-level load using SCADA systems for decades and this provides a very clear picture of the aggregated behavior of load. Most obvious in this data are the weekday, weather and diurnal sensitivities of load, which are the basis of system-level load forecasting tools [34].

Until recently, premises load data was only measured monthly and depending on the rate paid by the customer it might be only energy use (e.g., called interval metering) or peak power (e.g., ratchet demand rates). However the advent of advanced metering technology has offered the possibility for significantly more detailed sub-hourly premises load data that allows analysts to examine many shorter term behaviors such as device and equipment cycling at the sub-hourly horizon. Although end-use metering is still very limited, it does provide additional insights that contribute important sub-hourly information to the study of load variability [53].

Recent work has identified a distinctive spectral signature for power from wind turbines [54]. The technique was successfully applied to sizing storage for variable generation mitigation [55], reducing variable generation forecast uncertainty [56], and studying load control for variable generation mitigation [34]. It particular, there appears to be an opportunity to use variability spectra to create a library of end-use load signatures that will enable the study of both load and generation variability and support the design of demand response control programs that are better suited to mitigating variable generation. This area appears to be a potentially fruitful topic for research with numerous opportunities, including

- End-use signature development for load decomposition;
- Model identification for both duty-cycle phase and amplitude of sub-hourly load behavior;
- Identification of human-driven behavior and demand response sensitivities; and
- Identification of non-cyclic load variability phases and amplitudes for diurnal and seasonal behavior.

The response sensitivities based on spectral variability functions in particular appear to simplify the evaluation and analysis of variability generation and demand response impact questions. For example, the computation of the overall emissions or cost impact of a load shift of t hours can be estimated by the convolution

$$v(t) = \int_{-\infty}^{\infty} c(\tau) l(t-\tau) d\tau = (c * l)(t) \tag{2.1}$$

where $c(t)$ is the cost or emissions at the time t and $l(t)$ is the load. While in time domain this can be difficult to compute, in frequency domain it is comparatively simpler if the data is available:

$$V(f) = C(f) \cdot L(f) \tag{2.2}$$

where $V(f)$, $C(f)$, and $L(f)$ and the Fourier transforms of $v(t)$, $c(t)$, and $l(t)$ respectively. Given a library of both generation variability and load control signatures in frequency domain, the optimal demand response design problem might be significantly more tractable than previously thought.

Demand Response Characteristics

Loads exhibit a peculiar characteristics that is often not considered in benefits analysis but is highly relevant to the analysis of load control. The relationship between energy, load, and ramping is actually quite robust. Most demand response programs can exclusively affect either power demand in the short term or energy consumption in the long term. In every other respect energy, power, and ramping are strictly related to each other as

$$\frac{d}{dt}Energy(t) = Load(t) = \int Ramp(t)dt \tag{2.3}$$

and this relationship is not affected by conventional demand response control strategies. For example a DSM program may reduce energy consumption of the long term but the power and ramping impact are strictly a function of how the demand response program affects energy use. Similarly an air-conditioning load curtailment program to cut peak may reduce power during peak hours but the natural tendency of thermostatic devices to make up for short-term deficits over the long run means that long term energy use may be relatively unchanged. The characteristic time of a demand response control strategy and how the systems it controls respond are essential to understanding how well demand response will mitigate variable generation resources and the degree to which the demand response impact inequality will apply. From a controls perspective we recognize that full observability is achieved by measuring energy, while full controllability can only be achieved by actuating ramping.

The argument can be made that resources with greater ramping capabilities should be considered higher quality reserve resources. In ancillary services markets this characteristic places a premium on faster resources with downward substitutability. For this reason demand response resources that control the power of loads are at least as valuable as generation resources with the same net power response and often more valuable because of their greater ramping response and stronger downward substitutability. In fact it seems the principal and perhaps the only limiting factor on the ramping rate of demand response resources is the telecommunications latency of the control signals. The real-time market in the Olympic Peninsula had a typical delay of about one or two seconds in response to the market clearing event, but the market itself cycled only once every five minutes [5].

Summary of Impacts

The impacts of generation variability hence the benefit of load controllability may be summarized as follows:

- Long term load forecasts have lower relative RMSE than long term variable generation forecasts. Thus load can be expected to outperform the generation it mitigates, all other things being equal.

- Load control can be scheduled with greater reliability than variable generation and thus can be expected to outperform the generation it mitigates, all other things being equal.

- The loss-of-load probability impacts of variable generation are mitigated by load control in part by moving all controllable load out of the load impacted by outages.

- The capacity credit for controllable load can be expected to be comparable to the capacity credit for variable generation, if not better because for every 1 MW of load that is controllable, 1 MW of generation reserve can be decommitted.

- The standby capacity reduction associated with controllable load should in principle be 100% of the responsive load under control.
- When controllable load is dispatched under liberalized markets, consumers become the providers of resources. This tends to divert revenue from generators to savings by consumers. Based on the cost of variability on the supply side, this can be expected to be about 10-20% of the direct cost of electricity and mitigates the need to provide 5-10% additional installed capacity [57].
- The secondary emissions benefits for avoiding startup and part-load fossil generation are expected to be 10-20% for modest levels of variable generation (i.e., $< 20\%$) but may be significantly lower for some bulk systems, depending on conditions.
- The geographic sensitivity of load is different and very likely less than it is for variable generation. Loads tend to be more uniform and better diversified than variable generation.

2.2 Responsive Heating/Cooling Systems

This section discusses the characteristics and operation of heating cooling and ventilation loads in residential buildings. These systems are designed to perform several key functions in a home. The most important is to provide a steady and comfortable indoor air temperature. Modern forced-air systems also filter air, sometimes provide replacement fresh air, and if necessary a comfortable level of humidity. There are many different types of equipment that provide heating and cooling using forced air systems. Heating strategies vary more than cooling and can include in-floor radiant heating, baseboard heaters, and radiators. In all cases there is a source of or sink for heat and a way to transfer heat throughout the home.

In parts of North America where humidity levels can be extreme, i.e., over 90% or less than 20%, it is common for systems to include humidification or dehumidification equipment. This equipment can be zoned but typically humidification is done at the whole house level.

Homes less than 2500 ft^2 (230 m^2) usually only use a single zone served by a single heating or cooling heating/air-conditioning unit. Larger homes, especially those over 4000 ft^2 (370 m^2), typically have multiple zones, e.g., upstairs and downstairs. Each zone can be served by a separate unit, or two or more zones might share a single heating or cooling unit. Often the equipment installed varies for each zone and can include dampers, mixing boxes, and other devices to individually heat, cool, ventilate and (de)humidify the zones independently.

Residential heating and cooling systems are single speed gas or electric heating units with electric air-conditioning in about 60% of homes. In climates where the heating conditions are less severe heat pumps are preferred and compose about 30% of the market. About 10% of residential systems also support two speeds.

Forced air systems are the preferred method of conditioning homes because of the cost and efficiency advantages they present. These have been installed in homes for decades and have been the standard for homes since the early 1950s. Forced air systems can provide four major services in a single package: heating, cooling, ventilation/circulation/filtration, and humidity control. The most common are heating and cooling, although it is not uncommon to find cooling only or heating only in climates where this is possible. Circulation is a natural byproduct of forced air systems and is particularly useful for destratification to avoid hot or cold areas in homes. Ventilation is not very common except in homes that are very well sealed against

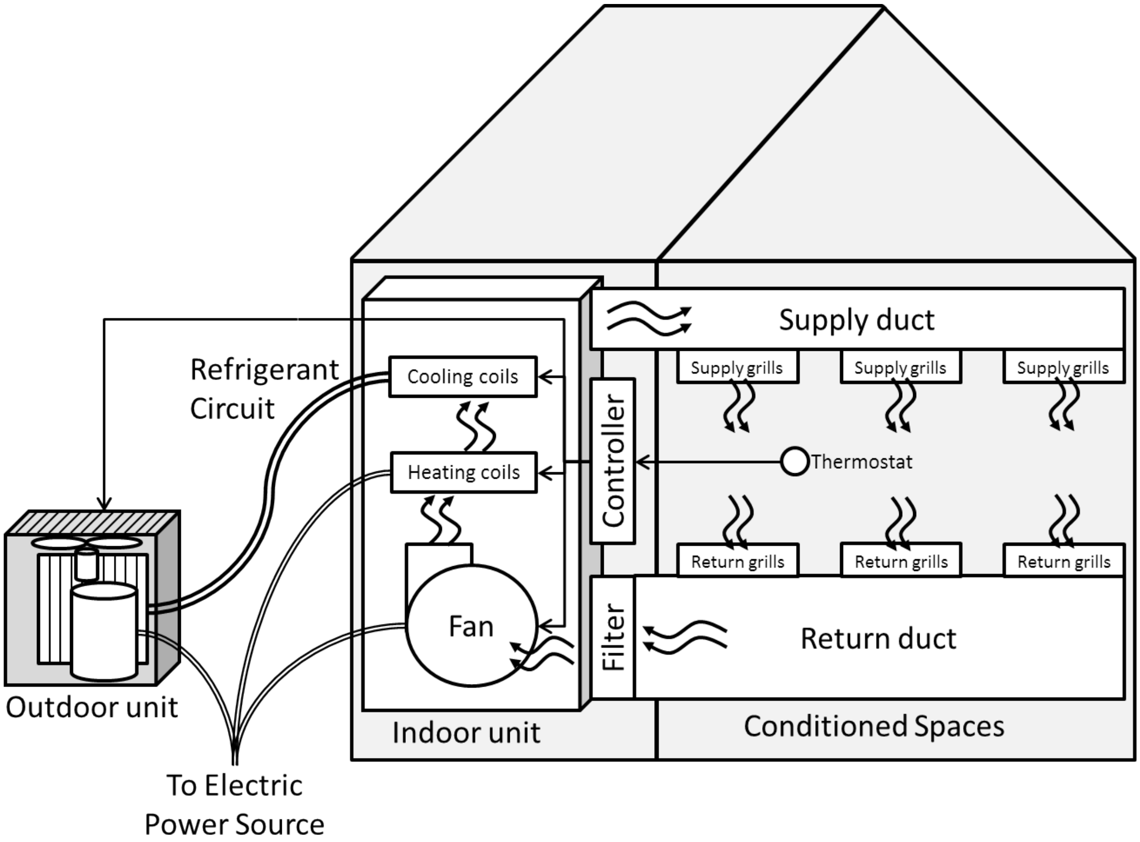

Figure 2.2: Basic heating/cooling system (Source: www.progreencompany.com)

leakage air. Filtration is becoming more common as homeowners become cognizant of the adverse health effects of dust and pollen. Humidification and dehumification is an option that is only used in cases of extreme humidity. The basic system operation shown in Figure 2.2 has not changed since it was first introduced. But the system complexity and efficiency have increasingly significantly over the years.

2.2.1 Control Automation

Automation has played an important role in the evolution of forced-air systems by providing better strategies for deciding when to turn various system components on and off. The thermostat is a key component of the automated control of heating and cooling systems and provides home occupants with control over the trade-off between

Figure 2.3: Classic Honeywell “round” thermostat

comfort and energy cost.

The earliest thermostat models had one temperature setting. If needed a mode switch was provided to specify whether the thermostat was to control heating or cooling based on this one set point. The classical Honeywell “round” thermostat shown in Figure 2.3 is one of the most commonly installed of these.

Over the years many features were added to thermostats to increase the convenience and comfort of occupants and improve the overall efficiency of heating and cooling operations. Today’s thermostat often include the following features.

Dual set points Two separate set points are supported, one for heating and one for cooling. These set points must be separated so that simultaneous heating and cooling cannot occur. Typically the minimum separation is twice the deadband or about 2°F (about 1.1°C).

Auto mode In this mode, the thermostat automatically chooses the heating or cooling mode based on the temperature set-points. In some thermostats, the fan runs at a lower speed in Auto mode when neither cooling nor heating is active.

Heat/Cool-only mode The dual set points make it easier to determine when heating mode and cooling modes are required, as with Auto mode. However occupants may want to prevent heating or cooling from operating. Selecting heat-only or cool-only mode prevents the excluded mode from operating. As with Auto mode, the fan may run at a lower speed when the system is not active.

Fan mode This mode disables both heating and cooling but keeps the fan running, possibly at a reduced speed.

Supplemental heat This mode engages the second stage heating system and raises the fan speed to maximum and it useful when the primary heating system has failed. This is sometimes referred to “emergency” heating, as opposed to “auxiliary” heating, which is automatically engaged when the primary heating system’s capacity is insufficient for conditions such as when the outdoor air temperature is too low for the heat-pump’s capacity.

Occupancy schedules Occupants can assign different set-points and fan mode for specific hours of the day and days of the week. At a minimum two occupancies are supported, such as *home* and *away*. Some thermostats have additional occupancies such as *sleep* and *vacation*, or customizable occupancies.

Overrides Sometimes the occupant wishes to directly set the temperature or mode temporarily. Overrides are usually set until the next scheduled occupancy begins or 3 hours if no occupancy schedules are defined.

Anticipators Some homes experience overshoot problems because of lags in the response. Older thermostat provided a heating feed-forward signal by running the current to the relay through a small coil placed near the thermostat coil but this strategy didn’t work for cooling. Modern thermostats sometimes include simple model learning components that compensate for lag in the thermal response and turn components on and off earlier, if necessary.

Some recently added features that are found today now include

Communications Communicating thermostats usually support wireless local area networks (e.g., 802.11 family of protocols). While the wireless protocols are standardized, the software protocols are not as standardized. Some better-known protocols are Honeywell, Nest, Zigbie, and OpenADR (1 and 2).

Home automation One of the key lessons from early advanced thermostat marketing was that people didn't really use them or understand them. Manufacturers like Nest seek to overcome this problem by making thermostats that detect and learn occupancy patterns instead of relying on consumer inputs. An alternative approach is to integrate the thermostat into a comprehensive home energy management system that is linked to the utility bill, taking advantage of the fact that homeowners are far more likely to make "good" energy management decision when they pay the bill.

2.2.2 Hierarchical Control

Participation of thermostatically controlled loads in demand response has to be considered in the context of existing and emerging electricity market mechanisms. The electric power industry has undergone a fundamental restructuring over the past 30 years, transforming from regulated to a market oriented system. Restructuring has entailed unbundling of vertically integrated organizations into independently managed generation, transmission and distribution systems. As a result electric power markets have been divided into wholesale and retail systems that interact according to a well-defined, albeit *ad hoc* design.

Most wholesale electric power markets are based on the design proposed by the U.S. Federal Energy Regulatory Commission (FERC) in its April 2003 white paper

[58] encompasses the following core features: 1) central oversight by an independent system operator (ISO); and 2) a two-settlement system consisting of a day-ahead market supported by a parallel real-time market to ensure continual balancing of supply and demand for power. The objective of an ISO/RTO is to ensure that supply equals demand at every instant, while maintaining system security and reliability and minimizing the total cost of serving the load. Optimization is performed on multiple time-scales. The day-ahead settlement system is a pure financial market for generators and load serving entities to create financially binding operating schedules. The real-time energy market allows for the physical exchange of power and addresses deviations between actual real-time conditions and contracted day-ahead agreements. The ISO solves security constrained unit commitment (SCUC) and economic dispatch (SCED) problems in both day-ahead and real-time markets to determine cleared supply and demand, and corresponding locational marginal prices (LMPs), which are reported to market participants. The ISO runs a balancing reserve market in parallel with the energy markets to calculate the cleared reserve capacities and the corresponding reservation prices needed to sustain operational balance at any every time interval.

Retail markets have not gone through such a restructuring process. Hence there is limited participation by distributed assets in wholesale markets through aggregation and there is no direct participation by smaller assets at all. However this can be expected to change with accelerated deployment of new smart grid infrastructure such as digital meters and advanced distribution control systems under the Smart Grid Investment Grants. Additionally, FERC Order 755 now requires grid connected short-term storage devices to be treated equitably as conventional generation units when providing regulation services. Similarly, FERC Order 745 required energy payment of demand response resources at nodal LMPs. But its status is somewhat uncertain in the wake of the US Court of Appeals decision limiting FERC authority to regulate demand response insofar as it impacts wholesale markets.

As a result a number of wholesale markets now allow distributed assets limited participation in energy markets. Usually these assets are used to meet peak load reduction or emergency services by drawing from large-scale demand response programs that serve commercial and industrial users. Feeder level resources still do not participate in wholesale markets, except when provided by demand response aggregators or in a limited number of pilot demonstrations projects. To realize the vision of an integrated demand response system at the wholesale level we must consider changes to wholesale market designs, deployment of a full-fledged system of retail markets, and linking those with wholesale markets in way that provides suitable incentives for participation by distributed assets.

There are two key elements to any proposed infrastructure that will facilitate robust and reliable electric power operations. The first is inter-scale infrastructure that allows devices at various topological levels to cooperate in determining the efficient allocation of the available resources. The second is the inter-temporal infrastructure that allows devices to distribute over subintervals of time the allocations they have received within a given time horizons. In its embodiment in DOE-funded pilot demonstration projects, transactive control addressed primarily integration over the structural hierarchy and left the problems of the temporal hierarchy to future research.

The transactive control infrastructure addresses this resource allocation and dispatch problem and is used to reconcile supply resource constraints with demand requirement, e.g., feeder constraints versus consumer comfort settings at the retail level. This is accomplished by using real-time prices as demonstrated in the Olympic Peninsula GridWise Demonstration project [5], and is also employed by American Electric Power in the Northeast Columbus gridSMART demonstration project [6].

These systems established retail markets that discovered the short-term price at which supply equals demand at each feeder in the distribution system given the current day-ahead prices and prevailing supply and demand conditions on the feeder and in the homes equipped with price-responsive devices. The Pacific Northwest Smart Grid Demonstration Project (PNWSG) uses a variant of this design for resource allocation that relies on mid-term forecasting usage instead of committing to short-term usage. The system also substitutes an index for a price to avoid the issues associated with trying to link with wholesale markets and use LPMs in regions that have neither at present. The PNWSG project also differs from AEP gridSMART project in the way the formulated signal is presented to the devices.

2.2.3 Transactive Control

The mismatch in the characteristic size, time, uncertainty of loads relative to generators of loads is a significant obstacle to using demand response to simultaneously displace generation-centric reliability services and mitigating generator market power: there are relatively few easily observed generators and their characteristic response times are relatively slow compared to overall system dynamics. Loads in contrast are far smaller, far more numerous, and for more difficult to observe but potentially far faster acting than the overall system dynamics.

The Olympic and Columbus demonstration were successful in achieving their primary objectives, i.e., they used transactive control to show 1) that thermostatic demand resources could contribute to short term capacity control using economic signals, and 2) that financial benefits would accrue to both utilities who installed and consumers who participated in such a control system.

Households recruited to participate in the Olympic and Columbus transactive control systems under the RTP tariff were equipped with home automation devices including a smart thermostat and a home-energy management system to integrate thermostats and other energy demand controllers with the utility metering system. The utility was equipped with a market-based dispatch system and communications links were established between the various components of the system. For both the Olympic and Columbus experiments an operations plan was developed to test the system and observe the response to price fluctuations resulting from wholesale price variations, distribution congestion and critical peak pricing (CPP) events.

Various scenarios were designed to elicit demand response such that one could estimate the technical and economic properties of the transactive system. Various utility value streams such as peak-load capacity deferment, reduced wholesale power purchase costs and revenues from operating reserves markets were estimated. Consumer impacts such as benefit, surplus, comfort and billing impacts could then be recovered. The operating scenarios generally involved continually exposing customers to small fluctuations in price as well as changing feeder congestion limits at various times to induce large price changes. The Olympic experiments were conducted from May 2006 to March 2007 in Clallam County and Port Angeles, Washington. The Columbus experiments were conducted from June through September 2013 in the northeastern area of Columbus, Ohio. Various combinations of feeder congestion limits and durations were tested. These were selected at various time of day, day of week, and weather. Additional critical-peak-pricing (CPP) responses were tested using selected CPP events.

Households who were recruited to participate voluntarily to the Olympic Peninsula experiment were offered the choice of two new tariffs: a time-of-use (TOU) price or real-time price (RTP). All customers received the same in-home equipment, including a smart thermostat and home-energy management wireless hub to establish connectivity to the utility's demand response dispatch system and provide 15-minute interval energy use metering. Some homes also received controllers for electric waterheaters and electric clothes dryers. Customers were then randomly assigned to the control group, a fixed price tariff, TOU or RTP. Regardless of the assignment, customers were promised on average \$150 benefit for participating 1 year. But they were told that the exact amount was uncertain and would be based on the tariff and how “well” they played the demand response “game”. Customers were given an income based on their energy consumption prior to the announcement of the program to which an additional \$37.50 incentive was added quarterly. The monthly energy bills under the experiment tariff were then deducted from that income. Any positive balance remaining at the end of each quarter was paid to them. During the experiment, customers continued to pay their normal bill to the utility and if customers overspent their quarterly income, they were not required to pay it back or carry the deficit into the following quarter.

Columbus customers were recruited from a pool of homes that already had smart meters installed. The smart meters provided 5 minute interval energy use data both to the utility’s metering system and to the home energy management system, which was installed to maintain connectivity with the utility’s demand response dispatch system. Customers were placed on an experimental RTP tariff approved by the Public Utility Commission of Ohio. Power was billed to consumers based on a commissioned-approved seasonal linear function of the wholesale LMP, plus feeder congestion costs, less a congestion rebate or a demand responsive incentive payment. All other taxes and fees remained unchanged.

In both projects, the demand curve was constructed from the bids received from the responsive equipment in households on the RTP tariff, as shown in Figure 2.4. Unresponsive load corresponds to all the other load on the feeder, including unresponsive equipment under RTP tariff, all other customers on non-RTP tariffs, services and losses. Bids were computed by the thermostats based on measurements of the indoor

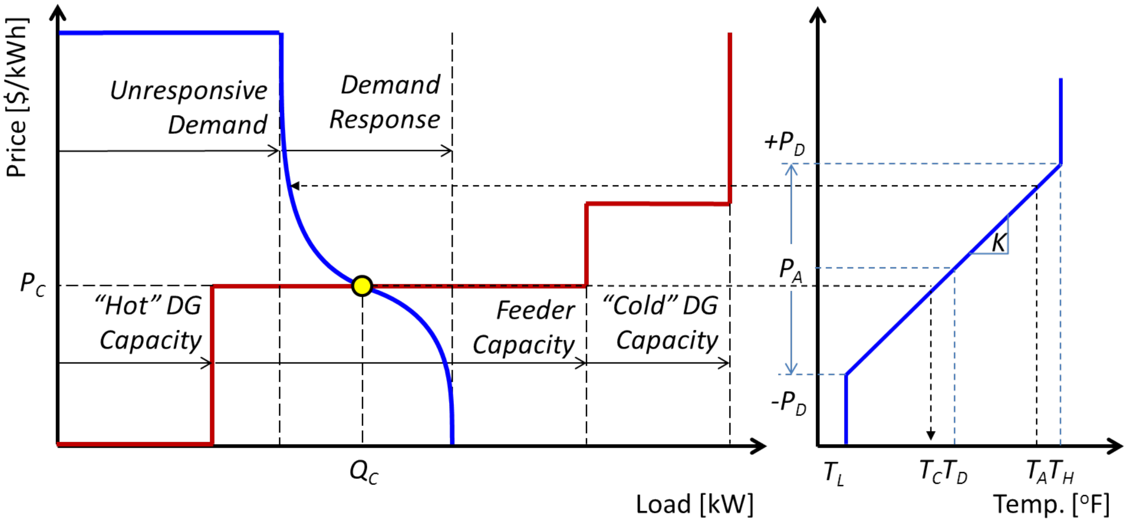

Figure 2.4: Capacity market clearing (left) and thermostat bid/set for cooling conditions (right) mechanisms

air temperature such that

$$P_B = \frac{kP_D}{T_M - T_D}(T_A - T_D) + P_A \tag{2.4}$$

where P_A is the long-term average price over the past 24 hours, P_B is the bid price, P_D is the long term price standard deviation, k is the customer's comfort control setting, T_A is the measured indoor air temperature, T_D is the customer's desired indoor air temperature, and T_M is the maximum cooling T_H or minimum heating T_L indoor air temperature allowed. The quantity $K = \frac{kP_D}{T_M - T_D}$ is referred to as the demand response control gain or comfort gain in \$/°F.

The supply curve was constructed from bids received by the various resources available, although in the case of the Columbus demonstration there was only the feeder supply. In the Olympic demonstration, supply included distributed generation with "hot" capacity representing must-run units that are already running and presumably can't or won't stop and any units that have zero marginal production cost, such as photovoltaic units. So called "cold" units are those that have start-up costs included in the marginal cost and therefore are held off until the demand is sufficiently high to justify starting them.

In all existing embodiments of the transactive control system the clearing price and quantity are found at the intersection of the supply and demand curves. The clearing price is then used to change the thermostat set point such that

$$T_C = T_D + K^{-1}(P_C - P_A) \tag{2.5}$$

where P_C is the cleared price, and T_C is the load control set point used until the next market clearing.

The total surplus is the left-side area between the supply and demand curves. The consumer surplus accrues to consumers not willing to forgo consumption at the cleared price. The producer surplus only accrues to those producers whose costs are below the cleared price. When the price clears above the feeder supply price, the utility collects a producer surplus from the feeder congestion. In the Columbus demonstration a congestion rebate returned the entire feeder surplus directly to the consumers while the incentive rebate compensated consumers who were curtailed as a result of congestion by diverting some of the utility's feeder surplus to pay the consumer's share of the deadweight loss caused by the withheld capacity.

Some criticize this congestion rebate as self-defeating in the long run. But it was deemed necessary as a compromise that would satisfy regulators and utility managers who were concerned about whether the tariff would be revenue neutral and unfair to the participating customers. In principle producer surplus from congestion on feeders is used to finance capacity expansion. However congestion charges only occur for those customers who reside in congested neighborhoods during congested periods. Utilities also laterally switch homes from one feeder to another to manage feeder loading so it may not be possible for a customer to “choose” where to live to avoid such charges. This introduces a potential issue of fairness in the sense that customers who sign up for the tariff may perceive they are paying a greater share of capacity expansion costs through scarcity rents than other customers. The congestion rebate was introduced to avoid charging only customers on chronically congested feeders for the cost of expanding capacity, which is an asset growth cost that is normally redistributed using blended tariffs. Customers who provide highly responsive resources are additionally compensated for curtailing under congestion through the incentive payment.

Although this compensation strategy does not seem likely to provide the desired long-term incentives to customers, it was hoped to have the desired effect in that it makes the bills “feel” more like a fixed price tariff in the long term while preserving the desired short-term incentives through savings opportunities not available to other customers. While this is consistent with the spirit of FERC Order 745, it is also quite evident that this is effectively a form of double compensation as critics of the order point out. In addition it would seem also to not be incentive compatible because a rational consumer would indicate a willingness to forgo that is higher than the true demand and one would observe a corresponding decrease in demand by the anticipated congestion fee. The incentives would seem to be wrong both in the short and the long term.

Long-term consumer preferences played an important role in determining the short-term outcomes of the demand response system. Newly-installed household equipment was configured with neutral defaults and customers were instructed how to enter their preferences. These preferences were an expression of the consumer’s willingness to forgo comfort in the very short-term for the benefit of a decrease in cost. Preferences could be set to a variety of values by participants depending on time of day and day of week. The preference setting resulted in a discrete choice to consume or not consume at a given price and thus formed the basis of both the bid price selection based on the prevailing conditions, i.e., higher bid prices for more comfortable conditions and lower bid prices for less comfortable conditions in the home. The aggregate effect of these comfort settings give rise to a logit-shaped demand curve that changes every 5 minutes as the states of the heating and cooling systems change in response to fluctuations in the price and other endogenous behavior in the home [6].

Detailed simulations of load control using thermostats revealed some potentially significant technical problems with the first embodiment of the transactive control system used in these demonstrations. Among these was demand response dispatch control drift. When the markets cleared the measured load was initially very close to the cleared load. However, during the five minutes that followed, before the next market clearing, the total load drifted away from the cleared load. This suggests that the 5-minute market implemented did not work well as a load dispatch "control" system. The prevailing hypothesis is that the drift is the result of changes in the diversity of thermostat states induced by a common exogenous signal. These changes in the state diversity of the loads were caused by the aggregate load's initial response to the change in price [59]. Because diversity always increases in the absence of an external forcing signal, the aggregate load tends toward the equilibrium load given the initial price signal and the prevailing conditions at the time the load is being observed. Under peak load conditions, this drift can be very significant, as illustrated in Figure 2.5, and can only be mitigated by a) minimizing the degree to which diversity is changed by the control signal, or b) preventing the devices from changing state during the 5 minute interval between price clearings. Because option (a) would defeat the purpose of the load control system, it would seem if diversity changes are the cause of the problem then option (b) is the only mitigation strategy available.

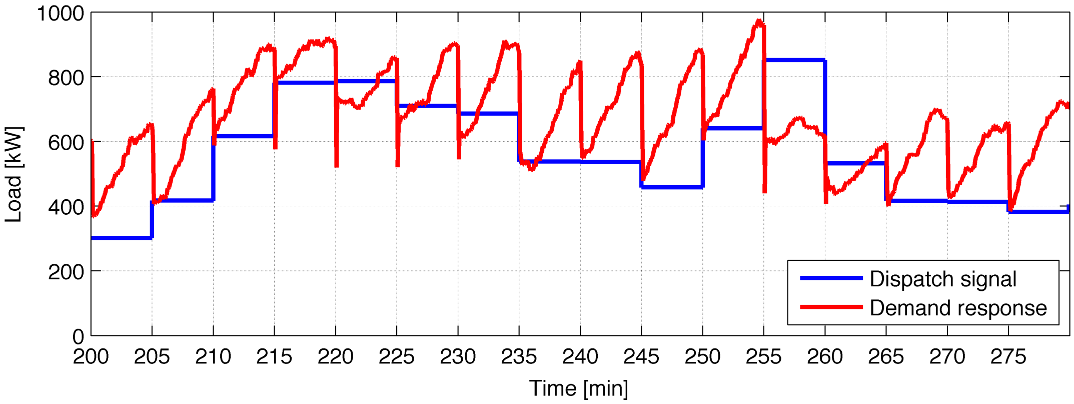

Figure 2.5: Example of drift in demand response using transactive control (Data courtesy Jason Fuller, Pacific Northwest National Laboratory)

2.3 Conclusions

The trend toward a more integrated and interconnected complex energy system is inexorable. Progress on the 21st Century's infrastructure of complex interlocking network of technical, social and economic energy systems is challenging our current understanding of these systems and our ability to design and control them. Significant challenges and research opportunities remain in load modeling and simulation, understanding the impact of consumer behavior on demand response, the fundamental theory for controlling widely dispersed demand response resources, and the verification, validation, monitoring and metering of demand response systems in utility operations.

Overall, it is clear that we are entering a period of increased electric utility receptiveness and growing innovation in the methods and strategies for turning a largely passive customer base into an active part of electric system operation. Technical innovation based on sound economic and social objectives as well as robust engineering design will be instrumental in bringing about this transformation.

The impact of controllable load on system operation can be deduced from studies on the impact of variable generation. The studies to date suggest that variable generation has both costs and benefits, and that the benefits outweigh the costs for reasonable mixes of variable generation relative to conventional resources. Many of the adverse impacts of variable generation are positive impacts for controllable load in the sense that the magnitude of the cost or impact as a function of generator variability is a cap on the magnitude of the benefit of load as a function of load controllability.

Controllable load exhibits the further advantage of high downward substitutability. Demand resources can be significantly favored under liberalized ancillary service markets. This feature of controllable load suggests that well-designed ancillary service markets along with market-based load control strategies could be a very powerful combination, provided the technical means of reliably controlling and aggregating load resources are available and employed.

The transactive control concept provides a market-like mechanism to aggregate and coordinate control of all the necessary resources, both supply and demand, at every level from transmission to end-use devices. This applies also to the various resource capabilities, energy, capacity, and ramping, at the necessary time-horizons from days-ahead to real-time. The comprehensive nature of the structure should alleviate the concerns of present day system planners and operators regarding controllability of distributed smart grid assets, allowing them to be fully incorporated into system operations to achieve multiple objectives:

- Higher utilization of generation, transmission, and distribution assets, by changing load behavior on peak;
- Lower wholesale market costs and power production costs, especially during high price periods;
- Lower ancillary service costs by engaging distributed assets to supply them;
- Lower cost for integrating new solar and wind generation them into system

operations by mitigating their variability and uncertainty; and

- Higher environmental benefits from more efficient asset utilization and the potential to easily internalize environmental costs.

- Increased reliability at both the bulk grid and distribution levels, from coordinated engagement of distributed assets across multiple operating entities by a) providing increased available reserve margins, b) incorporating them into bulk grid wide-area control schemes and c) integrating them with distribution level voltage control and reconfiguration schemes.

The transactive control concept increases the penetration of demand response and other distributed assets resulting from their significantly enhanced economic viability by allowing them to provide a complete set of services on par with traditional large-scale transmission-level resources. This control mechanism also helps sustain utility revenue requirements, stabilizes utility customer costs at low rates made possible by lower cost distributed assets that displace the need for additional conventional infrastructure. Thus the vision of enabling overall cost effectiveness and environmentally sound grid infrastructure is realized, while minimizing the information content of data transferred enhances overall cyber-security and customer privacy.

But in the short term transactive systems will be limited by the ability of the individual devices to respond quickly and correctly in a coordinated manner to signals emanating from the bulk system within the constraints imposed by the users of those devices [60]. By appropriate design of these devices we can enhance the speed and tracking of bulk control of demand response. The remainder of this thesis examines the design of devices that are linear time-invariant in the aggregate and therefore facilitate integration with other bulk system controls.

Chapter 3

The New Transactive Thermostat

In this chapter we use models to derive the requirements and specifications of individual thermostatic load controllers that can be described using linear time-invariant (LTI) models from a single input signal, e.g. a price, which is sent to all such loads periodically, e.g., once every 5 minutes.

The non-linearity of the aggregate load control model arises from the Schmitt-trigger behavior caused by the deadband or differential gap control in the household heating/cooling system thermostat. As an alternative to studying the non-linear behavior of aggregate load control systems, two possible approaches can be considered to create a load control system that is modeled as a linear time-invariant aggregate system. The first is to employ proportional feedback, e.g., by varying the fan-speed in place of differential gap control. This approach is very simple and lends itself well to treatment using classical control theory for continuous-time systems. But it has the disadvantage of being less efficient under part-load conditions because the reduced air-flow changes the temperature gradient through the indoor heat-exchanger.

The second approach is to use a discrete sampling interval and apply zero-deadband control only periodically, such as every 5 minutes when a new price signal is received.

The second approach is appealing because in every other respect the system performs the same as with a conventional non-zero deadband thermostat. Key elements of the system model become discrete but the system overall is nonetheless modeled as a linear time invariant system.

In this design we use a price P_C as the utility control signal and $t_s = 5$ minutes as the sampling interval, but it is understood that the solution is fundamentally the same for any single load control signal and sampling interval. To meet this design objective we propose a new thermostatic control architecture for residential buildings. We develop the building thermal model, the system model and various control elements for individual home heating/cooling loads. We show that houses equipped with the new thermostat are hybrid discrete-time control, continuous-time response linear time-invariant (LTI) systems that gives rise to an aggregate load control system that is a discrete-time system with a linear time-invariant response for time intervals less than 5 minutes.

3.1 Building System Model

The typical single-zone building system is illustrated in Figure 3.1. The building occupant sets a desired indoor air temperature set point T_D which is compared to air temperature T_A, given the indoor temperature control error E. When the temperature is too low or too high, the heating or cooling mode M, respectively, is selected by the thermostat contoller. The heat Q_H is added to or removed from the air in addition to other sources/sink of heat to/from the air, including the internal gains Q_I from appliances and occupants, the solar gains Q_S, and the envelope gain/loss $U_A T_O$. The building's air and mass respond to the heat Q_A added to the air, which we model using a second-order response model described below, and the air temperature T_A is

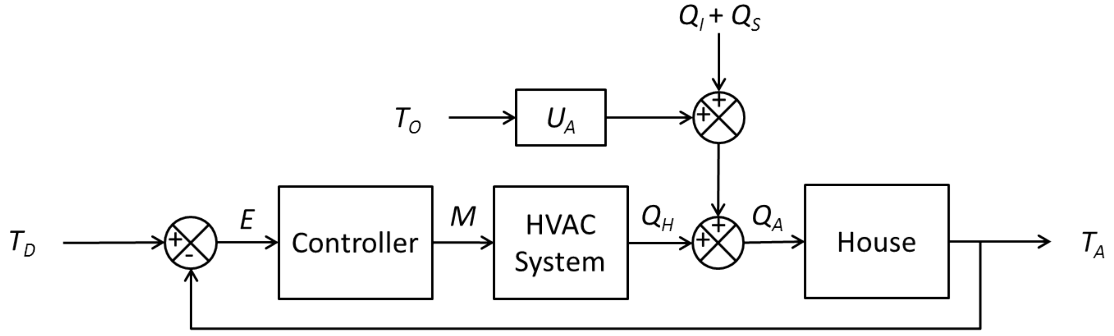

Figure 3.1: Conventional building air temperature control system

observed to close the feedback loop.

When a conventional thermostat is retrofitted for demand response two methods are generally used. The first is to simply interrupt the signal M and override the control of the heating/cooling system with a mode control signal M_C sent directly from the utility, as shown in Figure 3.2 (left). This direct load control method is widely used for emergency "one-shot" load relief programs and has the advantage of providing a relatively predictable amount of load relief for a population of loads based on the overall duty cycle. The disadvantage is that customers do not like giving up control of their comfort. Sometimes customers sign up just for the rebates and unsubscribe the first time the program is called, creating a potentially significant "free-loader" phenomenon. In addition, utilities do not like the load rebound that occurs when the load control program ends and hesitate to use direct load control for peak load management because the new peak loads can exceed the original peak that was to be mitigated.

A more consumer-friendly approach is to send a temperature offset signal T_C that raises or lowers the indoor temperature set point T_D to provide load relief for the time it takes for the house to reach the shifted set point's deadband, as shown in Figure 3.2 (center). This provides consumers with a limited degree of control insofar as the temperature will not go completely out of a given comfort band. It

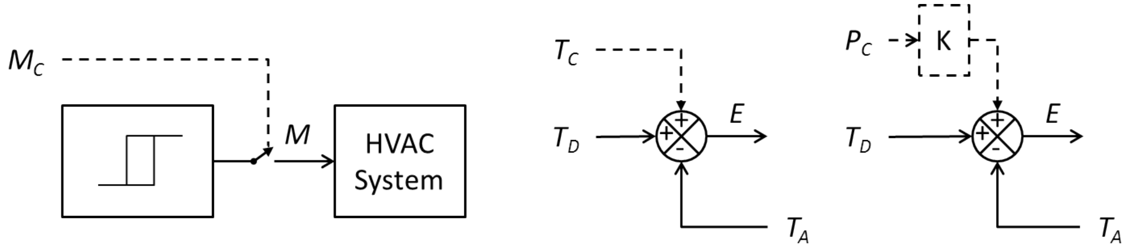

Figure 3.2: Direct load control by interruption (left), by thermostat offset (center), and by incentive signal (right)

also provides utilities with a modulated control signal, but utilities still suffer from the load rebound problem when the program ends. In addition utilities observe load control drift when the house indoor air temperatures moves into the regime of the new set point's deadband, which is likely to occur under peak load conditions or when prices are volatile, as illustrated in Figure 3.3.

Aggregate load drift and rebound arise from the evolution of individual device states during a demand response event. Prior to calling the demand response during period (a), the loads are fully diversified with their states uniformly distributed over the deadband range $T \pm \frac{1}{2}D$ and over the *on* and *off* states according to the duty cycle (here shown at 50%). This condition corresponds to an equilibrium regime with the overall "flow" of devices moving in a clockwise direction in heating mode and counterclockwise in cooling mode. When a demand response event occurs (here shown for heating mode), a signal is sent to all the devices that causes a reduction of the set point T_D by $\frac{1}{2}D$. The population of loads that ends up outside the upper bound of the deadband is immediately turned off while simulatenously an empty region of the deadband that was outside the lower bound is immediately opened up. The population is instantly redistributed according to the control strategy and a new significantly decreased load is observed (b). This condition is maintained for a time until the population begins to return to the new thermal and state equilibrium (c). When the new equilibrium is reached (d) it is sustained indefinitely until the thermostat offset

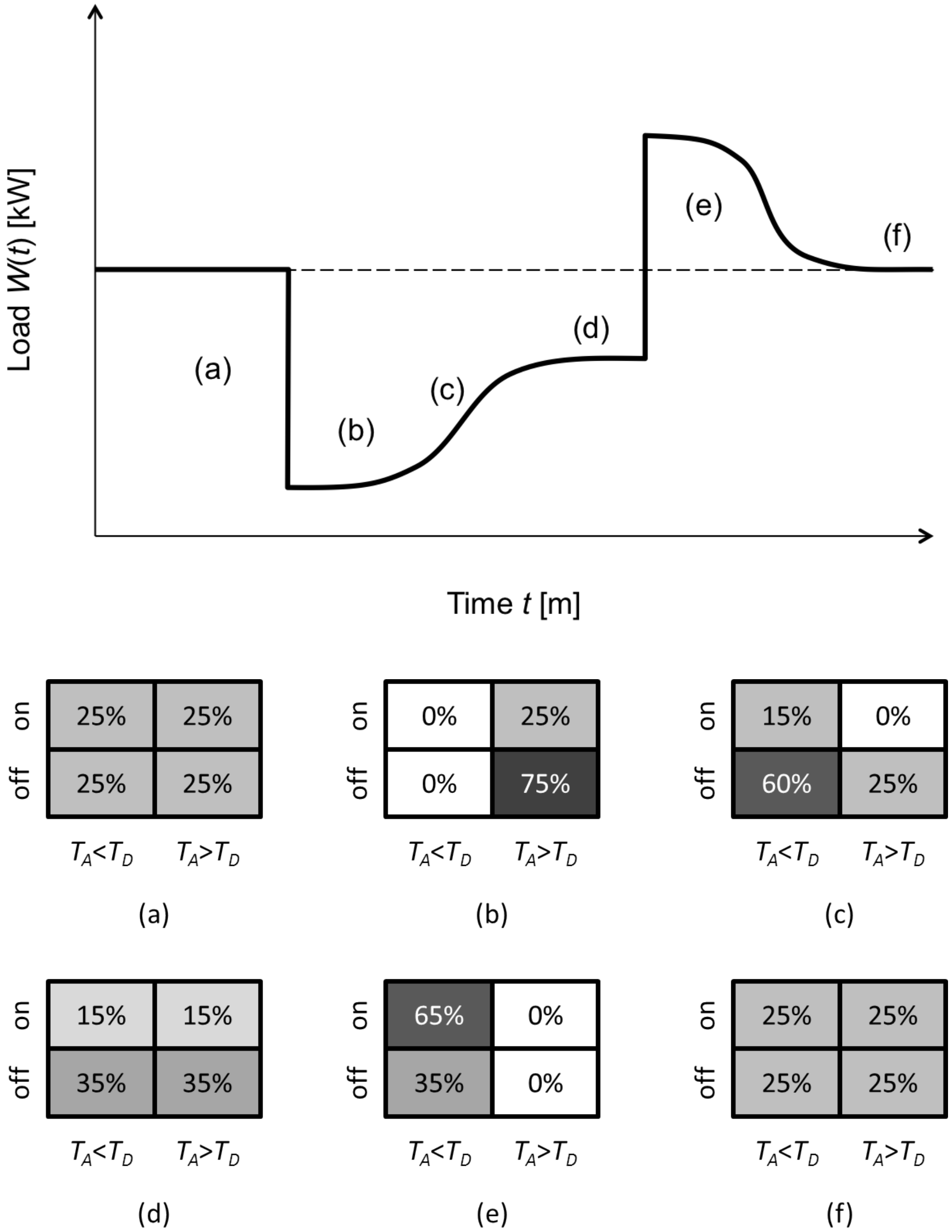

Figure 3.3: Thermostat set point control aggregate demand response event, showing aggregate load (top) and heating system state evolution for the population (bottom)

is released and the thermostat deadband reverts to its original position (e) and the process is reversed (f). Over a population of devices, the aggregate setpoint control strategies interact adversely with load deadband controls to cause uncontrolled drift in overall load during the periods (b) to (d) following dispatch and (e) to (f) following release.

Transactive thermostat designs improve on direct load control methods using incentive price-based control elements where the utility sends a real-time price signal P_C as often as once every 5-minutes, as shown in Figure 3.2 (right). The consumer sets a load control gain K that converts this price signal into a temperature offset that is added to the indoor temperature set point T_D. This has the advantage that it provides the consumer with a great deal of control over how much response they provide, as well as providing them a real-time economic incentive to respond. It also provides the utility a well-modulated control signal. However, depending on the type of controller used, the utility may still experience load control drift before the next price signal and/or load rebound when the next price signal is sent. This design will address these potential problems by modifying the controller's behavior to eliminate drift between updates of the incentive signal while maintaining full customer control of comfort.

3.1.1 Building Thermal Model

To evaluate the performance of building space conditioning systems in response to changes in the thermostat design we require a suitable model of the building thermal response. The typical residential building with a single-zone heating/cooling system is modeled using a general equivalent thermal circuit model, as shown in Figure 3.4. For sufficiently short time intervals the outdoor temperature, internal gains to the air and mass, and in particular the heating or cooling from the system are assumed constant.

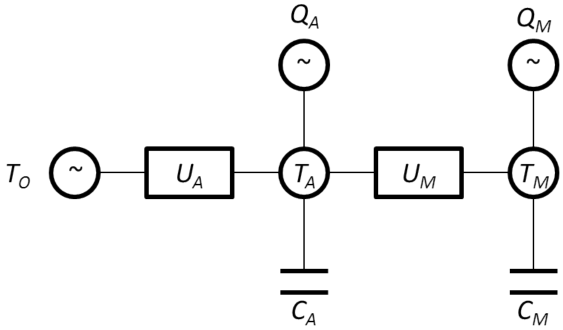

Figure 3.4: Equivalent thermal circuit for a residential building

For durations less than 5 minutes the model is derived from the air-mass heat balance equations

$$Q_A + U_A[T_A(t) - T_O] + U_M[T_A(t) - T_M(t)] + C_A\tfrac{d}{dt}T_A(t) = 0 \tag{3.1}$$

$$Q_M + U_M[T_M(t) - T_A(t)] + C_M\tfrac{d}{dt}T_M(t) = 0. \tag{3.2}$$

where

U_A is the constant conductance from the indoor air to the outdoor air (in Btu/°F.h),

C_A is the constant heat capacity of the indoor air (in Btu/°F),

U_M is the constant conductance from the building mass to the indoor air (in Btu/°F.h),

C_M is the constant heat capacity of the indoor air (Btu/°F),

T_A is the time-varying indoor air temperature (in °F),

T_M is the time-varying building mass temperature (in °F),

T_O is the constant outdoor air temperature (in °F),

$Q_A = Q_I + Q_S + MQ_H$ is the heat added to (or removed from) the indoor air (in Btu/h), and

Q_M $= 0$ is the heat directly added to (or removed from) the building mass (in Btu/h) and is assumed to be zero.

Solving these for $T = T_A - T_O - \frac{Q_I + Q_S + MQ_H}{U_A}$ requires that we derive the standard second-order differential equation for the air temperature in the house after a change in the heat output from the heating/cooling system[1]

$$a\ddot{T} + b\dot{T} + cT = d + fu(0) \tag{3.3}$$

where

a $= \frac{C_A C_M}{U_M}$,

b $= C_M + C_A + C_M \frac{U_A}{U_M}$,

c $= U_A$,

d $= Q_I + Q_S + MQ_H$ is the heat gain to the air and mass from all sources including the HVAC system in the mode $M = -1$, 0, 1, or 2 for cooling, off, heating and auxiliary, respectively,

f $= \Delta M \; Q_H$ is the magnitude of the step change in heat output from the HVAC system as it changes mode, and

$u(0)$ is the unit step function applied at the time $t = 0$ modulating the change in output from the heating/cooling system resulting from a change in the mode ΔM.

The internal gains $Q_I = Q_V + Q_O + Q_E$ should include the following sources or sinks of heat.

---

[1] It is convenient to also offset T_M although we do so without changing its notation.

Ventilation Air exchange with the outdoors can occur as a result of leakage due to wind and stack effects, forced ventilation from bath and kitchen fans and from dryer operation, and from open doors and windows. As a general rule, the number of air-changes per hour (ac/h) can be estimated from the vintage of the house, and is typically not less than 1/2 ac/h. This heat loss/gain can be included using

$$Q_V = \dot{V} C_A (T_O - T_A) \tag{3.4}$$

where $\dot{V}$ is the number of air-changes per hour for the building volume.

Occupants The presence of occupants generates both sensible and latent heat loads, roughly estimated at 120 Btu/h ($\approx$ 35 W) per person [61] or

$$Q_O = 120 N_O \tag{3.5}$$

where N_O is the number of occupants present in the house.

Enduse Loads Almost all energy consumption by equipment inside the house is converted to heat and should be added to the internal heat gains. When considering only electricity demand

$$Q_E = 3.412\ W \tag{3.6}$$

where W is the measured power consumption. Under certain conditions heat loss or gain goes directly to the envelope mass but we will assume that at peak conditions these are small relative to the conduction and other heat flows so that $Q_M \approx 0$.

Solar gains are separated from internal gains because they are weather dependent. Simulations generally obtain these values from external modeling sources such as typical meteorological year (TMY) data. The total daytime solar gains can be determined based on glazing area and orientation

$$Q_S = \rho_G \left[I_D(\tfrac{1}{2}A_V + A_H) + I_N \sum_N A_n \cos\alpha_n \right] \tag{3.7}$$

where

I_N is the normal direct beam irradiance on the N insolated glazing surfaces (in Btu/sf.h),

A_n is the area of each of the N glazing surfaces in the direct beam (in sf),

α_n is direct beam incidence angle on each of the N glazing surfaces in the direct beam,

I_D is the diffuse sky irradiance (in Btu/sf.h),

A_V is the total vertical glazing surface area (in sf),

A_H is the total horizontal glazing surface area (in sf), and

ρ_G is the glazing shading coefficient, including exterior (e.g., shading), intrinsic (e.g., transmissivity) and interior shading factors (e.g., window treatments).

The denominator of solution for the indoor air temperature T in s-domain takes the usual form for a second-order system, i.e., $as^2 + bs + c$ [62]. The thermal response of the house is always overdamped as the roots of denominator are real because

$$b^2 - 4ac = C_M^2 \left[1 + 2\frac{U_A}{U_M} + 2\frac{C_A}{C_M} \right] + C_M^2 \left[\frac{U_A}{U_M} - \frac{C_A}{C_M} \right]^2 > 0 \tag{3.8}$$

for all physically realizable values of U_A, C_A, U_M, and C_M. The solution to Equation (3.3) in the s-domain is thus

$$T(s) = \frac{T_0 s^2 + (\dot{T}_0 + \frac{b}{a}T_0 + \frac{d}{a})s + \frac{f}{a}}{s(s+p)(s+q)} \tag{3.9}$$

where T_0 and $\dot{T}_0$ are the initial temperature conditions and p and q are the negative real poles of the house's thermal response, with magnitudes

$$p = \frac{C_M\frac{U_A}{U_M} + C_M + C_A - \sqrt{C_M^2\left[1 + 2\frac{U_A}{U_M} + \frac{C_A}{C_M}\right] + C_M^2\left[\frac{U_A}{U_M} + \frac{C_A}{C_M}\right]^2}}{2\frac{C_M C_A}{U_M}} \tag{3.10}$$

$$q = \frac{C_M\frac{U_A}{U_M} + C_M + C_A + \sqrt{C_M^2\left[1 + 2\frac{U_A}{U_M} + \frac{C_A}{C_M}\right] + C_M^2\left[\frac{U_A}{U_M} + \frac{C_A}{C_M}\right]^2}}{2\frac{C_M C_A}{U_M}}, \tag{3.11}$$

for the air and mass, respectively. In time domain we obtain the solution to the air temperature

$$T_A(t) = T_p e^{-pt} - T_q e^{-qt} + T_\infty \tag{3.12}$$

where

$T_p = \frac{a\dot{T}_0 + bT_0 + d - aT_0 p - fp^{-1}}{a(q-p)}$,

$T_q = \frac{a\dot{T}_0 + bT_0 + d - aT_0 q - fq^{-1}}{a(q-p)}$, and

$T_\infty = \frac{f}{apq} + \frac{d}{c}$.

As a matter of convention q is chosen so that its magnitude is always greater than that of p. Then p represents the non-dominant pole for the response of the air and q represents the dominant pole for the response of the mass. In the typical house the mass response is sufficiently large with respect to that of the air that we find $q >> p$ by an order of magnitude.

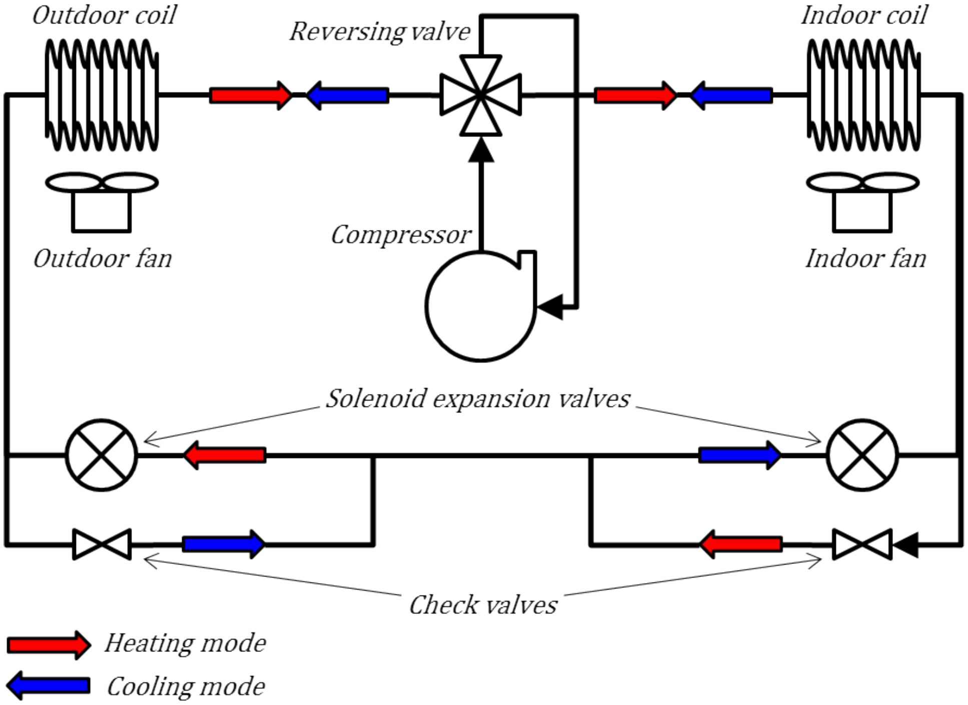

Figure 3.5: Air-source heat pump system diagram

This time-domain solution of Equation (3.12) is implemented in GridLAB-D Version 3.1 [23] used for simulations as discussed further in Chapter 4.

3.2 Residential Heat-pump Systems

The standard system design for a conventionally controlled residential heat-pump is shown in Figure 3.5. In general a thermostat monitors indoor air temperature which it uses to signal the heat-pump which mode to operate, depending on the occupancy. In conventional homes the thermostat operates as a standard Schmitt trigger with a roughly 1°F deadband which gives the hysteresis that is common to all residential thermostats.

3.2.1 Heat-Pump Systems

In normal operating modes for heating and cooling, the heat-pump's reversing valve and expansion valves are set to correctly direct the gas flow. When the thermostat calls for heating, the valves are set so that the indoor coils act as condensors and the outdoor coils act as evaporators. When the thermostat calls for cooling, the valves are set the other way around. Although the time required to reverse a heat pump is relatively short, it is not desirable because cycling between the two can lead to inefficient performance.

Auxiliary Heating

Auxiliary heating is supplementary heat provided when the lift of the heat pump is insufficient due to low outdoor air-temperature. It is unfortunate that auxiliary heating is employed when the temperature difference ΔT exceeds a certain limit, typically 2 or 3°F. This "trick" increases energy use during recovery following night-time set-backs. This increased demand and lower efficiency can be avoided if progressive set-ups are used or auxiliary heating is suppressed, but such "smart" recovery features are not always present in conventional thermostats. Note that while auxiliary heating is running, the normal heat pump continues to operate.

Emergency Heating

Emergency heating is provided when the primary heat pump fails. When emergency heating is employed the only source of heat is the auxiliary heating system and the heat pump system is disabled.

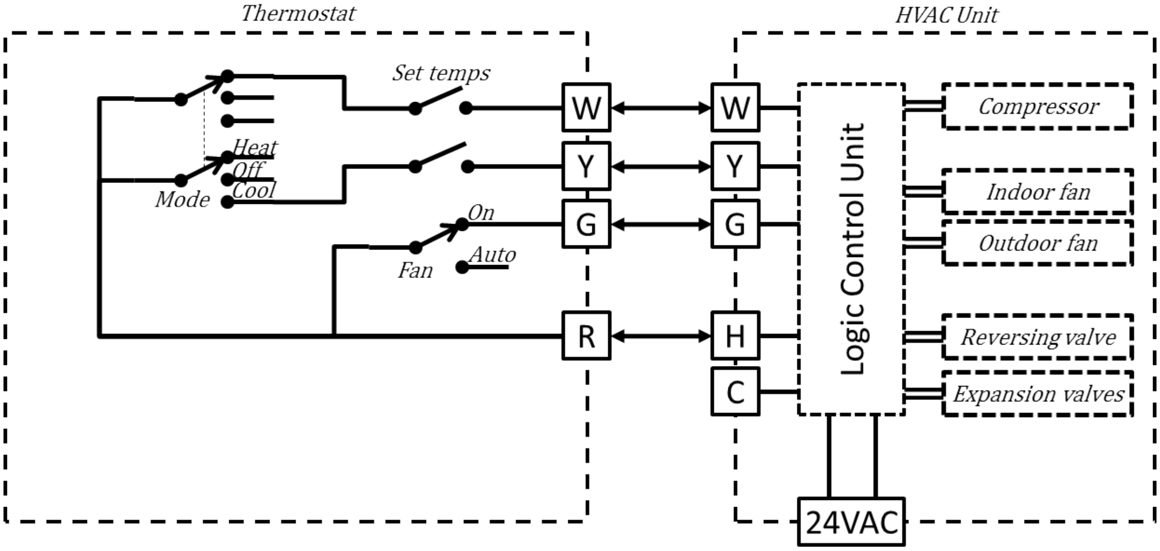

Figure 3.6: Conventional thermostat wiring diagram

Defrost Cycle

Defrost is required to remove ice build-up on the outdoor coils during heating when operated above 20°F and 60% relative humidity. During defrost, the system is briefly turned on in cooling mode while the outdoor fans are turned off. The defrost cycle can be controlled using a timer, measuring the refrigerant condition or by measuring the pressure drop across the coils [63].

3.2.2 Thermostat Control

Simple heat pumps only require separate fan, heating, and cooling control from the thermostat, as shown in Figure 3.6. The fan is operated when circulation, heating or cooling are required. Heating is operated when the indoor air temperature is too low and cooling is operated when the indoor air temperature is too high. Most thermostats can also control auxiliary or emergency heating directly (not shown).

Multi-Speed Control

Some residential indoor air handling units are equipped with a variable-speed drive that allow the air flow to be controlled continuously. In general this control allows low velocity circulation of air when the system is not heating or cooling. This continuous circulation help avoid air stratification and is done at reduced speed to save energy and reduce noise. When the heating or cooling is turned on, the fan speed is raised to deliver the optimal air flow across the indoor coil. Some system also use variable speed control to slowly accelerate and decelerate air flow when heat-pump heating or cooling is started and stopped. However, when auxiliary heating is started the fan is usually run immediately at full speed to avoid damage to the heating element. These multi-speed strategies are not modeled in this thesis.

Proportional Control

Variable speed fans in central air heat-pump systems offer the opportunity to provide continuously controllable heating and cooling to conditioned spaces in homes. However this is not generally done because of the efficiency loss resulting from part-load operation of the compressor and indoor coil heat exchanger. It remains an option for proportional control or part-load control of residential heating and cooling systems, particularly in circumstances where full-power operation can violate control performance standards. This mode of operation is not explored in this thesis.

3.2.3 Forced Air System Delays

One important modeling consideration are the delays associated with three aspects of forced air systems. These include the minute or so required for the heat-pump vapor circuit to reach thermal equilibrium, the delay associated with air ducting from the coil to the discharge registers, air mixing in the volume of the home, mass effects in

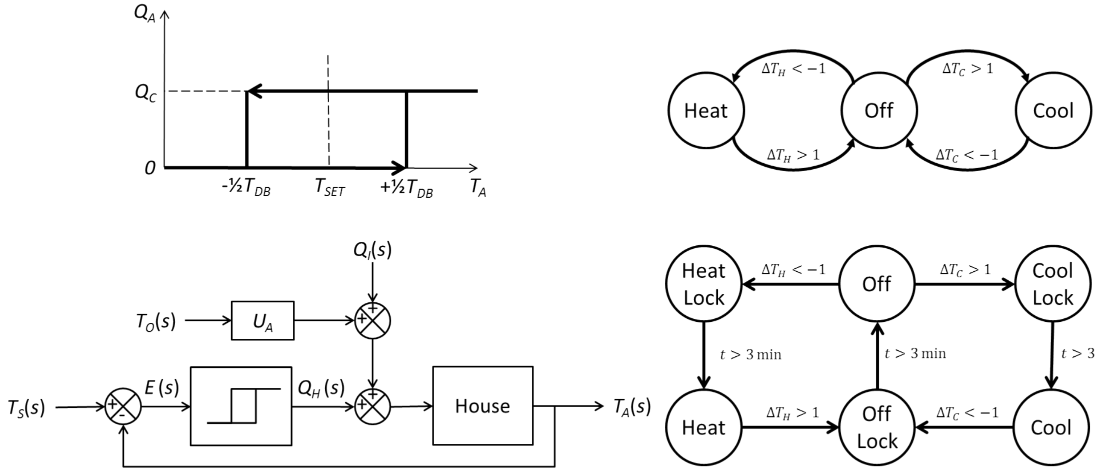

Figure 3.7: Conventional thermostat design (top left) and application (bottom left), deadband control (top right) and refractory state control (bottom right).

the immediate vicinity of the thermostat, and return air plenum delays. These delays can cause overshoot and many thermostats come equipped with so-called “anticipator” circuits to improve occupant comfort. These aspects of the new thermostat will not be examined in this thesis.

3.3 Conventional Thermostat Performance

The basic control design for a standard residential heating/cooling system is shown in Figure 3.7. This control strategy maintains the house air temperature close to the desired temperature chosen by the occupant. It is usual to find that the set point temperature changes depending on day of the week, the occupancy mode, e.g., home, sleep, away, vacation, or the operating mode, e.g., circulation, heat, cool, supplemental.

The main feature of this type of control is the differential gap D, also called the deadband, used to prevent the heating/cooling system from cycling too quickly as the house responds to the heat flows Q_H in and out of the air depending on the operating mode. The deadband is almost always constant for a particular thermostat design and it is usually large enough to prevent short-cycling of air-conditioners and heat-pumps, which have minimum run-time requirements to allow for pressure equalization before the next start and reduce motor wear and tear that occurs during compressor start-up with with non-zero vapor back-pressure.

When implemented using digital circuits, it is typical to find the set points are implemented with a deadband to synthesize the behavior found in analog thermostats rather than time-outs and lock-outs for refractory states, as shown in Figure 3.7.

3.3.1 Deadband Value

In principle the deadband is based on how much the indoor air temperature can be expected to change before the minimum runtime has elapsed, i.e.,

$$D = \dot{T}_A \times t_{min} \tag{3.13}$$

However, under mild outdoor conditions, the magnitude of $\dot{T}_A$ can be very large when the system is running. Similarly high magnitudes of $\dot{T}_A$ can occur under peak conditions when the system is not running. So this approach doesn't usually yield consistent values for reasonably likely conditions. For historical reasons stemming from how old mechanical bimetal and coil thermostats worked a differential gap of about 1°F (0.5°C) is typically used and most digital thermostats use that value even though they also have a minimum time lock-out of about 2 to 3 minutes to prevent short cycles resulting from direct user input of the set point.

In efficient digital thermostat designs one would expect that the deadband is not determined by the temperature bounds but by the optimal runtime required to maintain conditions within the comfort band provided. However, this does not appear to be a common practice.

Setting the deadband to nearly zero obviously results in a minimum runtime that is also nearly zero. Were it not for the lock-out time, the system would “fast cycle” at roughly a period equal to the feedback lag of the overall system.

3.3.2 Deadband Overshoot

A common problem is that the indoor air temperature is not uniform and it is possible for the thermostat measurement to lag the average air temperature enough to cause occupant discomfort. This problem used to be addressed using a small resistor placed under the sensor coil to create a feed-forward signal. While the heater is running the resistor was energized and would heat the coil causing the thermostat to turn the heat off earlier than it normally would. However, this feed-forward strategy didn't work for cooling modes. Modern thermostats use PID control loops and can avoid this problem by estimating system parameters using previous responses to minimize overshoot and determine how much lead time is needed to reach the desired set point at the specified time for a set-up or set-down of the temperature. If we assume that the mass is very near the air temperature, then from air heat balance in Equation (3.1) we have

$$\dot{T} = \frac{Q}{C_A} - \frac{U_A}{C_A} T. \tag{3.14}$$

and we find that for control during steady state the maximum overshoot for the minimum runtime is

$$T_{MO} = T_D + \left(\frac{Q}{C_A} - \frac{U_A}{C_A} T \right) t_{min}. \tag{3.15}$$

Another way a thermostat can overshoot the deadband is if the mass temperature of the building is not close to the air temperature. The mass then is heating (or cooling) the air while the system is heating or cooling, or conversely if it is also cooling or heating while the system is not heating or not cooling. This overshoot results from non-equilibrium conditions at the time the system changes state. Under steady operation and long-term setbacks/setups, conventional thermostats do not encounter this situation. If the thermostat set point is moved before the mass temperature reaches equilibrium then overshoot becomes more likely. This behavior is likely to contribute to some of the non-linearity seen in conventional thermostats that are retrofitted for fast demand response. In such cases we have

$$\dot{T} = \frac{Q}{C_A} - \frac{U_A}{C_A} T - \frac{U_M}{C_A}(T - T_M). \tag{3.16}$$

and the non-steady maximum overshoot for the minimum runtime is

$$T_{MO} = T_D + \left[\frac{Q}{C_A} - \left(\frac{U_A}{C_A} + \frac{U_M}{C_A} \right) T + \frac{U_M}{C_A} T_M \right] t_{min}. \tag{3.17}$$

3.3.3 Occupancy Schedule Set-Up/Set-Back

As noted above, conventional thermostats without setbacks use a temperature set point deadband that is typically on the order of $D \approx 1$°F and we expect that $|T_A - T_D| < \frac{1}{2} D$. Under normal heating/cooling conditions the mass temperature is very close to the air temperature so the likelihood of overshoot due to the initial condition $\dot{T}_0$ is very small. When the heating system turns off $Q = 0$, $T_A = T_D + \frac{1}{2} D$ and we have

$$\dot{T}_0 \approx -\frac{U_A D}{2 C_A}. \tag{3.18}$$

When the cooling system turns on $Q = -Q_C$ and

$$\dot{T}_0 \approx -\frac{Q_C}{C_A} - \frac{U_A D}{2 C_A}. \tag{3.19}$$

When the heating system turns on $Q = Q_H$ and $T_A = T_D - \frac{1}{2}D$

$$\dot{T}_0 \approx \frac{Q_H}{C_A} - \frac{U_A D}{2C_A}. \tag{3.20}$$

When the cooling system turns off ($Q = 0$) we have

$$\dot{T}_0 \approx -\frac{U_A D}{2C_A}. \tag{3.21}$$

Future work can take advantage of these relationships to estimate the key building performance parameters U_A and C_A based on temperature and electric usage measurements. Since the value of COP is relatively well known, the values of Q_H and Q_C can be estimated quite easily.

When a long-term temperature set-back (i.e., more than 1 hour since the last set-up) is started we have $Q = 0$. The temperature difference $T - T_M$ is typically not greater than $\frac{1}{2}$ the deadband which is presumably significantly less than the set-back offset ΔT, so in general

$$\dot{T}_0 \approx \frac{U_M}{C_A}\Delta T. \tag{3.22}$$

Similarly, when a long-term set-up is engaged to recover from a set-back, we have $Q \neq 0$ and the air and mass temperatures are approximately the old desired temperature T_D, while the new desired temperature is $T_D + \Delta T$. The initial condition $\dot{T}_0$ can then estimated as

$$\dot{T}_0 \approx \frac{U_M}{C_A}\Delta T + \frac{Q}{C_A} \tag{3.23}$$

where Q is either Q_H or $-Q_C$ depending on whether the set-up is for heating or cooling, respectively.

Future work can take advantage of these relationships to estimate the additional key building performance parameter U_M based on the response to set-back and set-up events.

Modern digital thermostats that implement setback/setup based on occupancy modes typically include so-called “anticipator” control elements to account for the lag in reaching the desired set point at the desired time. These control elements use estimates of the heating/cooling rate $\dot{T}$ such as those described above, typically using proprietary parameter estimation techniques. Occupancy set-back/set-up lead time is not modeled in this thesis.

In addition, to avoid less efficient operating modes thermostats should not engage supplemental heating during large heating season set-ups. Naturally, the thermostat must not engage heating of any kind during large cooling season set-backs.

3.3.4 Auxiliary (Supplemental) Heating Operation

Supplemental heating should be engaged only when outdoor conditions cause the heat-pump efficiency to fall below the 1.0 efficiency of the resistance heating coils, or when the lift of the heat-pump becomes insufficient to maintain the set point. Ideally the determination of this outdoor temperature should be based on system parameter identification, but even modern thermostats do not have such a capability, and often do not even measure outdoor temperature, so in general the decision to run supplemental heating is based on temperature differential exceeding a limit, e.g., 2°F (1°C) or runtime, e.g., $t_{on} > 1$ hour.

The impact of supplemental heating is to increase the value of Q_H. This behavior is modeled in this thesis and the electric load impact is modeled as well.

3.3.5 Emergency Heating Operation

The emergency operating mode is only engaged when the heat-pump system has failed. In general, this is done through manual input or occurs normally by virtue of supplemental operation without heat-pump operation. This behavior is not modeled in this thesis.

3.4 New Thermostat Design

The proposed thermostat design in its present embodiment is shown in Figure 3.8. Three inputs are provided to the thermostat. The consumer's indoor air temperature set point T_D and comfort preference K are set every few hours from an occupancy schedule established by the consumer. The real-time price P_C is sent by the utility every 5 minutes and is derived from various sources such as the hourly wholesale energy price signal, the real-time imbalance, and local capacity constraint prices, if any. The price signal is then filtered to separate the component with a time-constant that matches the building mass response and the component with a time-constant that matches the air's response, denoted as the slow response and fast response components, respectively. Both of these signals are then converted to a temperature offset using the consumer's comfort preferences. The slow response temperature offset signal is compared to the estimated[2] mass temperature T_M and added to the offset from the fast response signal. These are added to the consumer's desired temperature set point T_D, which is finally compared to the observed indoor air temperature T_A to determine the control temperature T_C. The signal is updated only when a new price received, which in the current embodiment is once every 5 minutes.

Once the control temperature T_C is determined, the remainder of the system is implemented in a manner that is consistent with conventional thermostats, and thus could be used to replace existing thermostat without changing the design of the rest of the HVAC system. The only difference with conventional thermostats systems is

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[2] The mass temperature T_M is estimated from the system mode M, the air temperature T_A and its derivative $\dot{T}_A$ using Equation (3.3), but the specifics of this observer are not in the scope of this thesis.

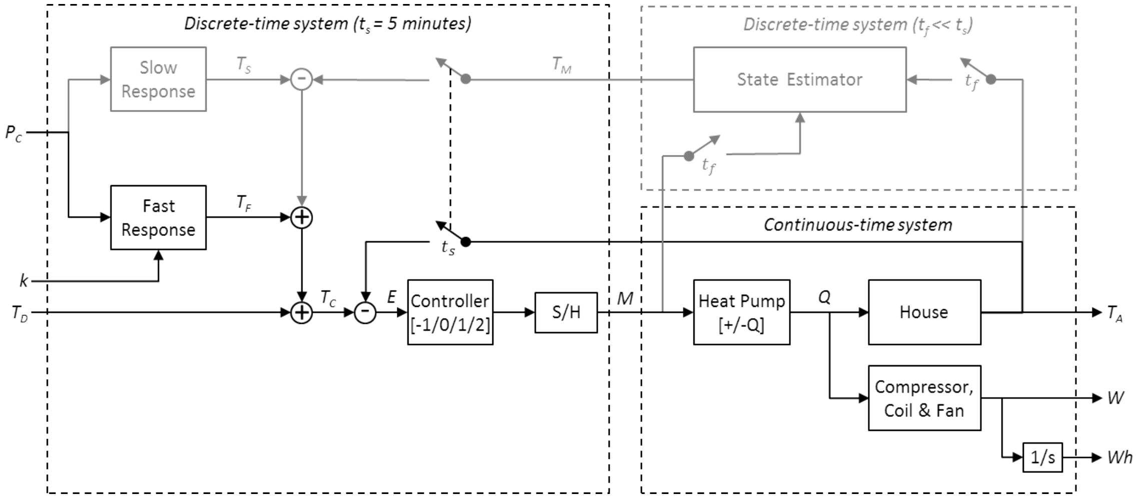


Figure 3.8: Proposed new thermostat design

1) the controller output M is held for 5 minutes, and 2) there is no deadband in the controller input E and therefore no hysteresis in the mode output M.

This design recognizes that a house has two fundamental responses, a fast one for the air and a slow one for the mass. In addition, it recognizes that any price signal from the utility may have multiple components, including a short term price signal emanating from distribution capacity or ancillary service markets, and a long term price signal from bulk energy markets. The purpose of the new thermostat is to control the long-term response of the house based on the bulk energy price independently of the short-term response of the house, which is based on the distribution capacity or ancillary service price signal. The focus on this thesis is on the fast response component of the thermostat design. The slow response control will be considered in future work.

There are potentially other components to the response of a house, such as the ramping response, that are not controlled by this design. At this time the price signals are not expected to arrive frequently enough (e.g., $t_s < 1$ minute) to allow control of a house's ramp response anyway. Such signals are not expected to include any primary regulation components for the foreseeable future. So both this signal and the

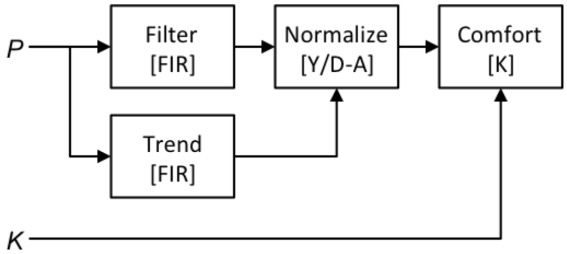


Figure 3.9: Slow response controller design

associated ramp response are not addressed by this thesis. Similarly, very long term price signals, such seasonal or annual changes in the energy price or the fixed price are not considered by this design.

The controller design process will require design of the following components. The slow response components will be designed in future work, while the fast response components will be the subject of this thesis. The remained of this section describes the main elements of the control system design in more detail.

Slow Response Controller: The slow response controller applies a low pass filter to the incoming price signal to remove any subhourly components. Based on the filtered input signal and the consumer's comfort preference, a temperature offset will be output, which is compared to the estimated mass temperature to determine what change to the mass temperature is required. This conceptual design of this controller is shown in Figure 3.9 but it is not in the scope of this thesis.

Mass Temperature Estimator: The air temperature is sampled quasi-continuously (relative to the price signal) and its derivative is estimated using a band-limited differentiator. The air temperature, its derivative and the system mode are then used to estimate the mass temperature and the house model parameters, i.e., second-order system's poles. The mass state estimator is not in the scope of this thesis.

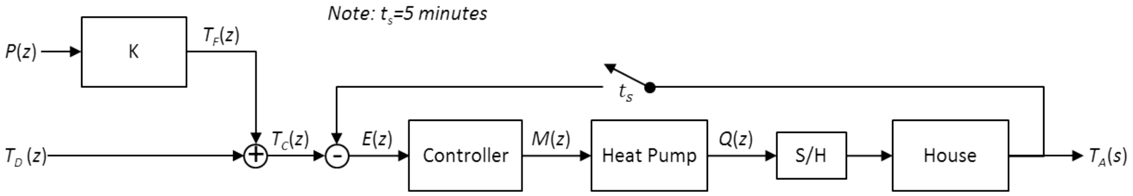


Figure 3.10: Fast response controller design ($t_s = 5$ minutes for all discrete-time control elements)

Fast Response Controller: The fast response controller applies a high pass filter to the incoming price signal to remove any hourly or greater components. Based on the input signal and the consumer's comfort preference, a temperature offset will be output, which is added to mass temperature error and the desired temperature before being compared to the feedback indoor air temperature. Because this thesis only addresses the fast response system, the filter is omitted from the analysis and focus is only on the comfort gain K, which is provided by the consumer to manage their comfort preferences. The system design including this comfort-only controller is shown in Figure 3.10.

System Mode Controller: The HVAC system mode controller uses the temperature error to determine whether cooling, heating and auxiliary heating is required and is in the scope of this thesis, as shown in Figure 3.10.

The remainder of this chapter will address the design of the fast-response controller. This capacity response controller is based on the Olympic controller design except that it uses a high-pass filter to remove the super-hourly components of price variations. This maintains only the input signal that can be reasonably responded to by the air in the building.

3.4.1 High-Pass Filter

The filter is designed based on a 5-minute price sampling interval. A finite-impulse response filter is initially proposed to avoid the pitfalls of feedback filter design in spite of the additional processing requirements. The order of the filter will depend on how far back the price history must go and the desired delay in the filter. A 48th order filter is used to balance these considerations. The filter cut-off frequency will depend on the time constant of the building mass. We use mass pole q of the building to determine the frequency cut-off for the high-pass filter.

For the simulation studies used in this thesis, a high-pass cut-off frequency corresponding to a 1-hour thermal mass time constant is used. Because the simulation generates price data by sampling a normal distribution every five minutes, the spectrum of the price does not contain any significant low frequency components relative to the high frequencies. We avoid simulating the high-pass filter by generating a Gaussian short-term price signal with the desired characteristics of filter output and the filter is not implemented in this thesis.

3.4.2 Comfort Gain Parameter

The customer's comfort setting K will serve as the gain for the capacity response controller. The comfort parameter determines the gain of the input price signal. Because the system is a LTI and the comfort gain is on the input only and is not in the feedback loop, it is unnecessary to consider the impact of the gain in the performance studies themselves. All the results will be linear within the saturation limits of the hardware. For the purposes of this thesis, the comfort gain will be set constant at $K = 1$ for all study cases.

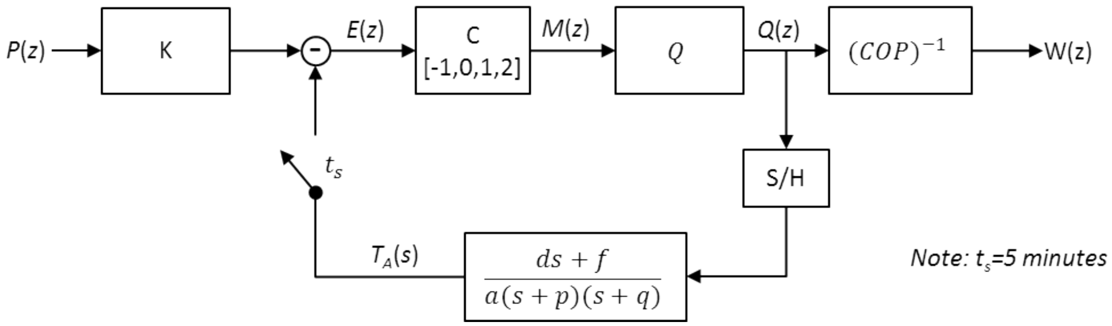


Figure 3.11: Diagram of subsampling response of the new thermostat

Table 3.1: Fast response of load control for $t < t_s$

Mode	**M(z)**	**Q(z)**	**COP**	**Response** (kW^2.h/\$)
Cool	-1	$-Q$	2.0	$\frac{1}{2}KQ$
Off	0	0	$-$	0
Heat	1	Q	3.0	$\frac{1}{3}KQ$
Aux	2	$2Q$	1.0	$2KQ$

3.4.3 House Price Response

The overall response of the house to a changed price signal can be derived from the system diagram in Figure 3.11. The overall load control transfer function for this system for $t < t_s$ is

$$\frac{W(z)}{P(z)} = \frac{KQC}{(COP)} \tag{3.24}$$

The response for the various system modes are shown in Table 3.1.

The design response of a typical house is illustrated in Figure 3.12. These vector field plots show the evolution over 5 minutes of both the mass and air temperatures for a range of conditions in a typical house where both temperatures are in the neighborhood of the set point temperature. The neutral mass response condition $\dot{T}_M = 0$ is also shown, as indicated by the dotted line $T_M = \frac{U_A}{U_M}T_A + \frac{1}{U_M}Q$. Under steady conditions, the sub-hourly fluctuations in the price signal $P(z)$ are expected to be Gaussian and should not significantly change the mass temperature because

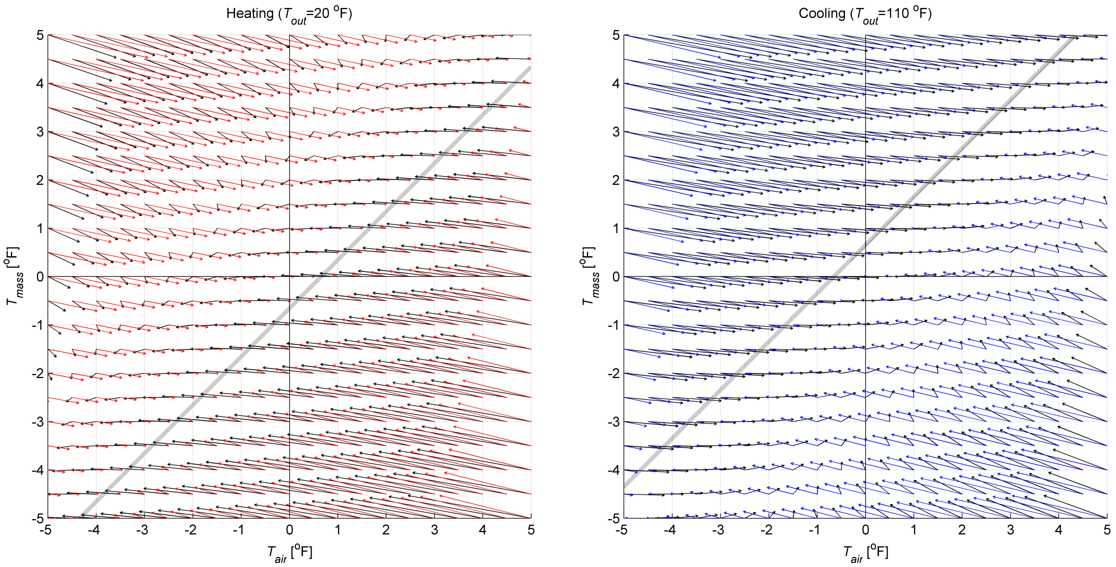


Figure 3.12: House heating (left) and cooling (right) design response for system on (red/blue) and off (black) with neutral-mass response condition (dotted)

by design any long-term fluctuation in the price is filtered and used to control the mass temperature separately from the short-term response of the air temperature. In general we can continue to assume that $T_M \approx T_A$. Then the response to a set-back or set-up event is no different than it is for conventional thermostats as discussed Section 3.3.3. As a result, excessive mode cycling is not expected to occur more frequently under steady state conditions than it does with a conventional thermostat.

However, outdoor air temperature changes, changes in internal and solar gains, as well as setback/setup schedules are expected to change the mass in ways that the price signal can oppose. To address these issues, mode cycling control must be established to prevent the load control system from engaging modes in the short-term that are counterproductive or inefficient in the long-term. Unfortunately, these controls also have the effect of changing the expected response of the load control system in ways that cannot be studied using the current simulation tools. Therefore these protections will be disabled and the extent to which they occur can be evaluated in future work.

3.5 Control Performance Metrics

In this section we develop the control performance metrics for the individual loads. These metrics will be used to design individual thermostats that meet performance objectives that can be reasonably expected by utilities and determine the limits of demand response performance in general. Because the aggregate load model is simply the sum of the individual LTI models, we can easily extrapolate the aggregate load performance from the response of the individual models.

3.5.1 Comfort Control Performance

The control performance of a single house is estimated for prevailing TMY conditions over a 4 week period using the indoor air temperature errors with respect to the set point schedule.

Temperature Overshoot

Although the short-term fluctuations in the indoor temperature set point do not significantly impact the mass temperature, any long-term trend in the price is expected to cause a change in the mass temperature that would noticeably affect the indoor air overshoot in the time interval t_s. The simulation is constructed to preclude these mass effects until closed-loop mass temperature control can be introduced in later work. Using Equation (3.15) we can evaluate the temperature overshoot as a function of mass temperature

$$T_{MO} = T_N + \left(\frac{U_M}{C_A} t_s\right) T_M. \tag{3.25}$$

where $T_N = \left[\frac{Q}{C_A} - \left(\frac{U_A+U_M}{C_A}\right) T_D\right] t_s$ is the neutral mass condition, i.e., the condition where the mass temperature does not change over the time interval t_s.

Mean Temperature Error (MTE)

The mean indoor air temperature bias error is computed with 1 minute sampling of temperatures as

$$\text{MTE} = \frac{1}{N_T} \sum_{t=1}^{N_T} [E(t)] \tag{3.26}$$

where N_T is the number of temperature samples taken, E is the total temperature deviation, including the load control offset.

Mean Temperature Deviation (MTD)

The root mean squared indoor temperature error is computed with 1 minute sampling of temperatures as

$$\text{MTD} = \sqrt{\frac{1}{N_T} \sum_{t=1}^{N_T} [E(t)]^2} \tag{3.27}$$

3.5.2 Energy and Cost Performance

Daily energy use and costs are computed based on whole-house metering (which include other end-use loads) and the prevailing prices.

Mean Daily Energy (MDE)

The mean daily energy computed daily at midnight using interval energy metering and is given by

$$MDE = \frac{t_s}{N_D} \sum_{k=0}^{N_T} W(k) \tag{3.28}$$

where N_D is the number of days over which the simulation is run.

Mean Daily Cost (MDC)

The mean daily cost is computed using the prevailing tariff (fixed or real-time price) depending on the scenario as

$$MDC = \frac{t_s}{N_D} \sum_{k=0}^{N_T} W(k)P(k) \tag{3.29}$$

Mean Cost Deviation (MCD)

The cost variance can be used to determine whether short term price volatility results in disproportionate cost variation. The mean daily cost deviation is computed as

$$MCD = \frac{1}{N_D} \sqrt{\sum_{k=0}^{N_T} \left[W(k)P(k)t_s - MDC\right]^2} \tag{3.30}$$

3.5.3 Compressor Wear and Tear

The wide variation in $\dot{T}$ when the set point is changed *before* the building mass has reached thermal equilibrium with the air presents a number of important challenges that conventional thermostats do not address. It seems inappropriate to retrofit conventional or modern digital thermostat with demand response inputs that are expected to operate faster than the mass time-constant of roughly one hour. The challenge addressed by the new controller is that demand response system must include protective control elements to reduce potentially damaging mode cycling due to the large and fast set point changes relative to the mass response of the building induced by short-term RTP volatility arising from distribution capacity management and regulation services required by the grid.

Excessive heating/cooling mode cycling can be a problem if the controller output switches from cooling to heating or from heating to cooling in less 24 hours, or about the time constant of the building's mass. This time is somewhat arbitrary, but seems reasonable for all but the most extreme weather fluctuations. However, the current controller design does not attempt to restrict fast mode cycling so that its prevalence can be evaluated to determine whether it is a significant concern (see Section 3.5.1). Because the long-term price signal is not changed in the simulation studies this is not expected to affect the results.

Chapter 4

Experiment Design

This chapter describes the design of the numerical simulation experiments used to test the performance of the new thermostat. The reference house design is described, including the loadshapes, occupancy schedules, heat-pump design, control systems and the locations in which the experiments are run. Then a model system of 7 homes with no parameter diversity is described. Finally the price signals used to dispatch demand response needed to determine control performance and outcomes are described.

The overall structure of the real-time price demand response experiments is illustrated in Figure 4.1 (left). For each study the location, house design specifications

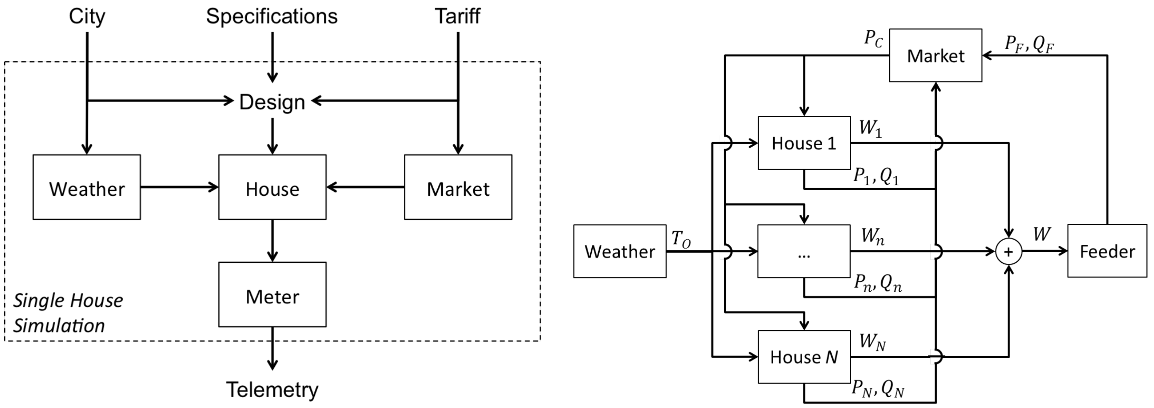


Figure 4.1: Single house model (left) and utility feeder model (right)

and tariffs are used to produce a single house model, the performance of which is observed using thermostat and metering telemetry in the simulation. At the utility level, a feeder is simulated with real-time pricing based on the transactive control system used in the Olympic and Columbus projects as shown in Figure 4.1 (right). In transactive control systems the homes submit bid prices and quantities P_n and Q_n to the market to build the demand curve. The feeder submits the cost P_F and available capacity Q_F to build the supply curve. The clearing price P_C is then determined by the market and sent to the homes to reset the thermostat setpoints. However, this thesis focuses only on the open-loop behavior of the utility's demand response control system by examining only the response of the aggregate load W to a change in the clearing price P_C within the time interval of a single price signal, i.e., less than 5 minutes. The longer term closed-loop behavior of the utility demand response control system will be examined in future work.

It should be noted that the unit conventions in this chapter include both imperial and metric units. As a general rule, imperial units are used for heat (Btu/h) and temperature (°F) in the context of heating and cooling equipment design and operation, while metric units are used for power (W) and energy (W.h) in the context of electricity demand and prices.

4.1 Location and Weather

The numerical experiments are conducted in 3 study cities located in the continental United States. Seattle is in a northern cool climate and is chosen for mild winters amenable to demand response using heat-pumps and mild summers for which demand response will be very limited. Phoenix and Miami are in southern hot climates, the former with dry summer conditions and the latter with humid conditions, both of

Table 4.1: Cities and climate conditions

City	**TMY File**	**Timezone**	**Low** (°F)	**High** (°F)	**Solar** (Btu/sf.h)
Seattle	WA-Seattle.tmy2	PST+8PDT	23	98	326
Miami	FL-Miami.tmy2	EST+5EDT	38	93	330
Phoenix	AZ-Phoenix.tmy2	MST+7	27	115	340

which will challenge air-conditioning demand response.

4.1.1 Reference Cities

For the study cities Typical Meteorological Year (TMY) data is used and their timezones are shown in Table 4.1. The TMY method [64] is usable in the studies because each contiguous data block in TMY data file covers an entire month, with temperature discontinuities only present at the month boundaries. None of the studies will span a month boundary so no higher-order outdoor air or solar gain disturbances are expected in the boundary conditions for the house thermal model.

Depending on the location, the homes are expected to consume between 60 and 70 MBtu annually based on the local energy code. Widely varying contribution to space conditioning costs for heating and cooling are expected based on the locale. Thermostat setback schedules are employed. Service hotwater is provided by electric resistance coils. Based on the 2012 International Energy Conservation Code (IECC) [65], the expected end-use energy consumptions for the model home are shown in Table 4.2.

4.2 Reference House Design

The reference house design is a two-storey structure with a crawlspace and an attic. The space conditioning unit is an all-electric direct expansion heat-pump with a single

Table 4.2: IECC end-use energy for model home in study cities

End-use	**Seattle**		**Miami**		**Phoenix**	
	(MBtu/y)	(%)	(MBtu/y)	(%)	(MBtu/y)	(%)
Heating	11.7	18.6	0.6	0.9	3.1	4.4
Cooling	2.9	4.6	20.9	31.9	21.6	30.7
Fans	3.3	5.3	5.2	7.9	6.5	9.2
Hotwater	13.7	21.8	7.6	11.6	7.9	11.2
Lighting	4.9	7.8	4.9	7.5	4.9	7.0
Plugs	26.3	41.9	26.3	40.2	26.3	37.4
Total	62.8	100.0	65.5	100.0	70.4	100.0

Table 4.3: House design

Parameter	**Seattle**	**Miami**	**Phoenix**
Floor area (sf)	2400	2400	2400
U_A (Btu/°F.h)	536	431	431
C_A (Btu/°F)	1017	1017	1017
U_M (Btu/°F.h)	11154	11154	11154
C_M (Btu/°F)	4122	4122	4122

speed compressor and fan, which are sized according to the design conditions for the study cities, Seattle, Miami and Phoenix.

The basic house thermal parameters are chosen so that building code complies with the performance-based energy code, as allowed for by the IECC code. The thermal parameters of the reference house are derived by GridLAB-D using the thermal model developed in Chapter 3 with overall performance summarized in Table 4.3.

4.2.1 End-Use Load Shapes

Internal gains are based on hourly ELCAP load shapes [66], as shown in Figure 4.2. Because the ELCAP load shape data does not include subhourly fluctuations, the model in this thesis assumes that internal gains are constant for any given 5-minute interval during which the response to a change in price is considered.

Modifications to the 1993 ELCAP load shapes are necessary to bring the magnitudes

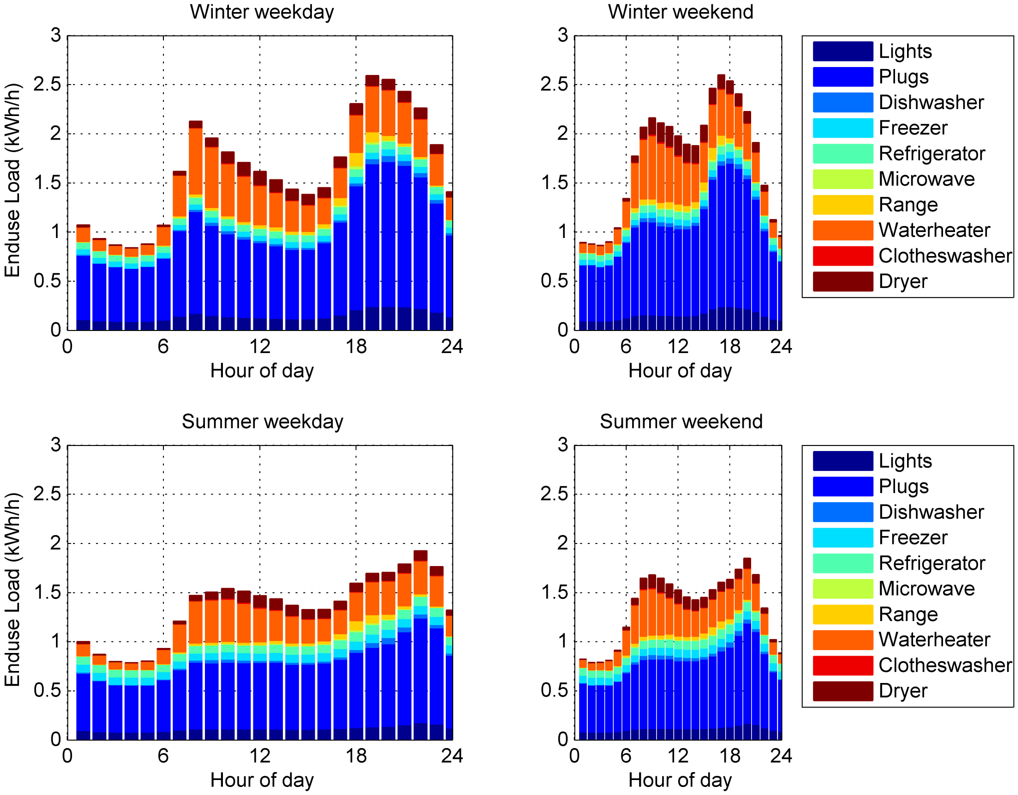


Figure 4.2: 1993 ELCAP loadshapes adjusted with 2013 RBSA demand levels

up to date based on the 2013 Residential Building Stock Assessment (RBSA) load surveys by the Northwest Energy Efficiency Alliance (NEEA). These are shown in Table 4.4 [67]. The magnitudes of the daily energy use of each end-use was adjusted to match the RBSA 2013 survey results. However, the overall 1993 ELCAP shapes of the loads are similar to the new RBSA shapes and were not changed. The RBSA load surveys cover only the Pacific Northwest region but the occupancy-driven diurnal end-use load shapes generally are consistent over most regions of the United States, include Miami and Phoenix. Regional differences in lighting schedules and waterheater standby losses are not considered significant relative to the total load and internal gains in the context of this study.

Table 4.4: ELCAP loadshapes update with RBSA results

		Winter			Summer	
End-use	**ELCAP**	**RBSA**	**Change**	**ELCAP**	**RBSA**	**Change**
	(kWh/d)	(kWh/d)	(pu)	(kWh/d)	(kWh/d)	(pu)
Lights	See note (1)	3.62	–	–	2.75	–
Plugs	14.47	21.71	1.50	11.00	16.50	1.50
Dishwasher	0.36	0.60	1.66	0.31	0.60	1.95
Freezer	3.68	1.40	0.38	5.03	1.91	0.38
Refrigerator	3.90	1.68	0.43	4.60	1.98	0.43
Microwave	See note (2)	0.17	–	–	0.14	–
Range	1.43	0.80	0.56	1.14	0.64	0.56
Waterheater	14.34	8.03	0.56	11.21	6.28	0.56
Clotheswasher	0.31	0.15	0.50	0.28	0.14	0.50
Dryer	3.12	2.00	0.64	2.56	1.64	0.64

Notes:

(1) In ELCAP lights and plugs are combined

(2) In ELCAP all cooking is combined

Table 4.5: Occupancy and thermostat set point schedule

Occupancy	**Weekday**	**Weekend**	**Heating** (°F)	**Cooling** (°F)	**Comfort** ($/°F)
Night	20:00–6:00	23:00–7:00	68	76	1.0
Home	6:00–8:00,18:00–22:00	7:00–23:00	72	78	1.5
Away	8:00–18:00	–	66	80	0.5
Vacation	–	–	–	–	–

4.2.2 Occupancy Schedules

The residential occupancy schedule is chosen for a typical dual-income family with 2 children in school, as shown in Table 4.5. The occupancy comfort settings are based on the settings observed in the Columbus demonstration, as shown in Figure 4.3.

4.2.3 Indoor Air-Temperature Set Point

The indoor air temperature set points are normally on a setback schedule. The simulation studies employ setback schedule suitable for a two-worker middle-income

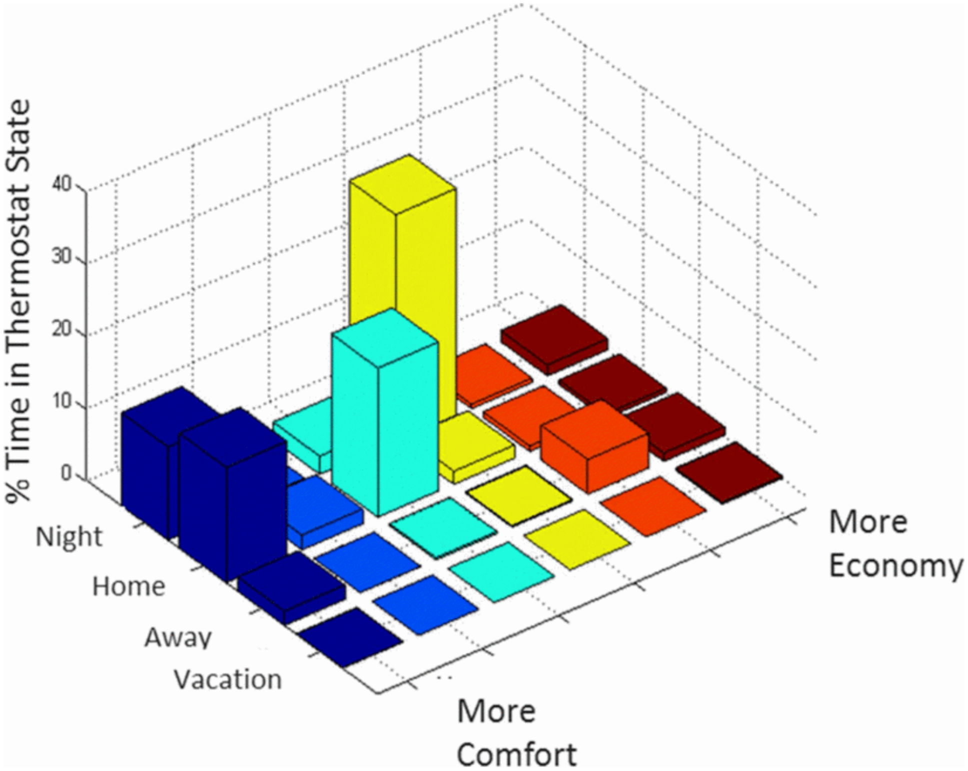


Figure 4.3: Columbus demonstration project comfort settings (Source: Steve Widergren, Pacific Northwest National Laboratory)

family with children in public school, as shown in Table 4.5.

4.3 Heat-Pump Sizing

The heat-pump system capacity is based on the larger of the cooling and heating design capacities.

4.3.1 Cooling Capacity

The cooling capacity is determined by the cooling design conditions for each city, i.e., maximum internal gains, maximum solar gains, and maximum outdoor temperature. The cooling capacity must satisfy the steady state heat balance. From Equation (3.1) we find

$$Q_C = U_A T_C - U_A T_D + Q_I + Q_S + Q_O \tag{4.1}$$

where the following are given at the design condition at the peak cooling hour of the year

Q_C is the cooling design capacity

U_A is the effective envelope conductance

T_D is the desired indoor air temperature

T_C is the outdoor temperature,

Q_I is the total internal heat gains,

Q_S is the total solar heat gains,

Q_O is the total occupant heat gains,

In addition a 30% latent heat load factor is included for Miami to account for high humidity under the cooling design condition.

4.3.2 Heating Capacity

The heating capacity is determined by the heating design conditions for each city, i.e., minimum internal gains, no solar gains, and minimum outdoor temperature. The heating capacity must satisfy the steady state heat balance for at worst 20°F, or

$$Q_H = U_A T_D - U_A \max(T_H, 20^\circ\mathrm{F}). \tag{4.2}$$

where the following are given at the design condition at the peak heating hour of the year

Table 4.6: Heatpump design criteria and capacities for study cities

Parameter	**Seattle**	**Miami**	**Phoenix**
T_H (°F)	23	38	27
T_C (°F)	98	93	115
Q_H (Btu/h)	60	54	66
Q_C (Btu/h)	60	54	66

Q_C is the cooling design capacity

U_A is the effective envelope conductance

T_D is the desired indoor air temperature

T_H is the outdoor temperature,

These values are given in Table 4.6.

4.3.3 Auxiliary Heating Capacity

The auxiliary heating is sized such that it satisfies the heating design capacity required to provide emergency heating (no heat-pump contribution) at the peak heating design condition

$$Q_X = U_A T_D - U_A T_H. \tag{4.3}$$

These values are given in Table 4.6.

4.3.4 Design Capacity

The larger of Q_H and Q_C determines the heat pump design capacity for both and is designated as heat pump capacity Q_H for the remainder of this thesis. Because none of the heating design conditions are below 20°F, the auxiliary unit capacity Q_X is the same as the heating design capacity, as shown in Table 4.6.

Table 4.7: Salt River Project (SRP) inclining block rates in Phoenix

Block (kWh)	**May-Jun Sep-Oct** (¢/kWh)	**Jul-Aug** (¢/kWh)	**Nov-Apr** (¢/kWh)
< 700	10.57	11.17	8.03
$700 - 2000$	11.25	11.78	8.03
> 2000	12.31	12.03	8.03

4.4 Electricity Prices

The customer cost of electricity varies according to the tariff employed to compute electricity price. Three tariffs are used in this study, one for customers paying conventional fixed energy price, one for customers paying time-of-use prices, and one for customer paying real-time prices.

The tariffs used in the study differ from those extant in the study cities to facilitate direct comparison of regional response signals with otherwise comparable characteristics. For example, in Seattle the average price of electricity was 9.6 ¢/kWh in August 2014. Customers in Miami paid around 12.1 ¢/kWh in the summer of 2014. Customer in Phoenix paid an inclining block rate as shown in Table 4.7. However, for the purpose of making results comparable the same tariff structures are used for all three study cities with price adjustments to maintain revenue neutrality as follows.

The revenue-neutral time-of-use (TOU) tariff was designed first using a methodology that requires an optimization of the form

$$\begin{aligned} \underset{P_L,P_H}{\text{minimize}} \quad & [(R_F(P_F)-C_F)-(R_T(P_L,P_H)-C_T)]^2 \\ \text{subject to} \quad & 0 < P_L < P_F < P_H \qquad \text{(a)} \\ & 2P_L < P_H \qquad \text{(b)} \end{aligned} \tag{4.4}$$

where

$R_F(P_F) - C_F$ is the net revenue from customers on the fixed price tariff,

$R_T(P_L, P_H) - C_T$ is the net revenue from customers on the TOU tariff,

P_L is the off-peak price of the TOU tariff, and

P_H is the on-peak price of the TOU tariff.

The constraint (b) is applied to ensure that the on-peak price is sufficiently high with respect to the off-peak price that it induces demand response.

It is important to observe that although *net* revenue neutrality is intended, consideration of the cost change of serving the aggregate load is not necessary because the tariff design assumes no change in the consumer's response, thus no change in the load, and thus no change in the cost. Therefore for the purposes of the tariff design the objective function can be simplified to $[R_F(P_F) - R_T(P_L, P_H)]^2$.

The constraints in Equation (4.4) do not lead to a unique solution. However, a unique solution can be found by further constraining P_L as a function of the fixed price P_F, which we choose to be 2/3 to resemble the TOU tariff used in the Olympic study. In this case the tariff design problem is simplified to

$$\begin{aligned} \underset{P_H}{\text{minimize}} \quad & [R_F(P_F) - R_T(P_L, P_H)]^2 \\ \text{subject to} \quad & P_L = \tfrac{2}{3} P_F \end{aligned} \tag{4.5}$$

The study model is greatly simplified by using the same TOU tariff for all studies. The TOU tariff design is performed for Seattle winter and summer cases only using the fixed price of 8.1 ¢/kWh, which was used for the Olympic study. The fixed prices of the Miami and Phoenix summer-only studies are then adjusted to achieve revenue neutrality by solving the problem

$$\underset{P_F}{\text{minimize}} \quad [R_F(P_F) - R_T(P_L, P_H)]^2 \tag{4.6}$$

Table 4.8: Fixed price tariffs for study cities

City	**Tariff** (¢/kWh)	**Difference** (%)
Seattle	8.10	–
Miami	7.88	−2.7
Phoenix	8.24	+1.7

The revenue neutral real-time price (RTP) tariffs are obtained for each city by computing the value of the mean real-time price P_A which satisfies the objective

$$\underset{P_A}{\text{minimize}} \quad [R_F(P_F) - R_R(P_A, P_D)]^2 \tag{4.7}$$

where

P_A is the average real-time price,

P_D is the standard deviation of the real-time price and

$R_R(P_A, P_D)$ is the revenue from customers on the real-time price tariff.

The solutions to these three optimization problems are given in the following sections.

4.4.1 Fixed Price Tariff

The fixed price tariffs obtained are shown in Table 4.8. The tariff in Seattle is set at 8.1 ¢/kWh so that results can be compared with the results of the Olympic project. The Miami and Phoenix fixed price tariffs are changed compared to the Seattle tariff so that the TOU tariff is revenue neutral for all three cities according to Equation (4.5). The prevailing fixed rate in Ohio during the Columbus study was 8.64 ¢/kWh.

Table 4.9: Seasonal time-of-use rates

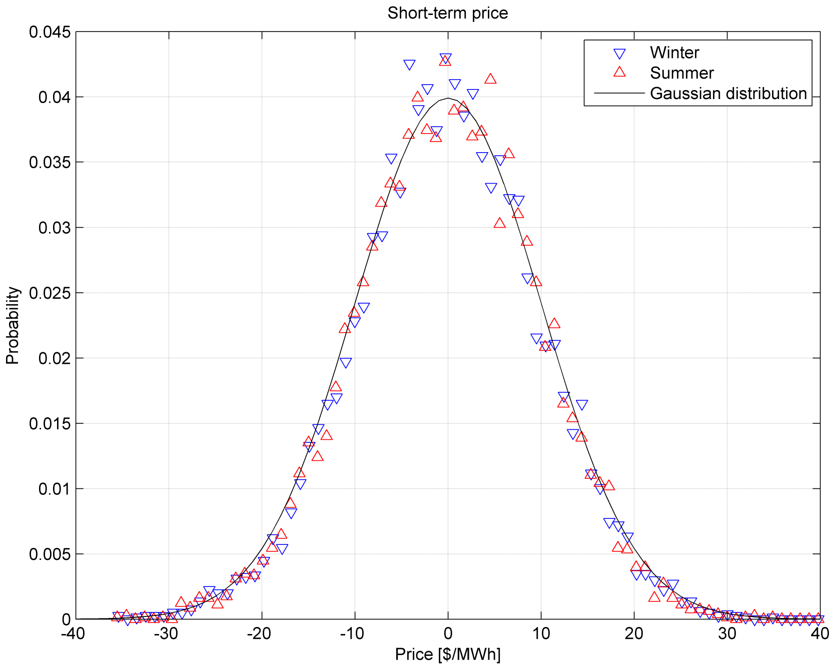
Season	**Period**	**Times**	**Price** (¢/kWh)
Winter	off-peak	9:00 – 18:00 & 21:00 – 6:00	5.40
	on-peak	6:00 – 9:00 & 18:00 – 21:00	11.53
Summer	off-peak	21:00 – 15:00	5.40
	on-peak	15:00 – 21:00	13.81

4.4.2 Time-of-Use Tariff

The time-of-use (TOU) tariff for all three cities is based on the high-differential tariff design used for both heating and cooling seasons used in the Olympic demonstration project, as shown in Table 4.9. The winter tariff is used only for the Seattle winter study. The summer tariff is used for all three cities' summer study. Both these tariffs satisfy Equation (4.5).

4.4.3 Real-Time Price Tariff

The real-time prices received by the thermostat are filtered so that the long-term trend from the LMP is not present and only the short-term price volatility is present. For the purposes of this study, the short-term relative volatility of the real-time price is set at $P_D/P_A = 12.4\%$. The distribution of the short-term price compared to the ideal Gaussian distribution is shown in Figure 4.4 (top). The long term prices can be obtained using a low-pass filter, e.g., an order 144 finite-impulse response (FIR) with normalized cut-off frequency at $\pi/12$ rad/sample. The residual quantity is the short-term price signal, i.e., $P = P_{LMP} - P_A$, as shown in Figure 4.4 (bottom), where P_A is the long term price and satisfies Equation (4.7). In the model for this thesis the short-term price is generated by a Gaussian random variable with mean P_A and



Seattle Winter (¢/kWh)	Seattle Summer (¢/kWh)	Miami Summer (¢/kWh)	Phoenix Summer (¢/kWh)
8.084	8.084	7.873	8.222

Figure 4.4: Short-term RTP volatility (top) and RTP means (bottom)

standard deviation $P_D = 0.1235 P_A$.

4.4.4 Revenue Neutrality

The tariffs are designed to be revenue neutral without demand response, as shown in Table 4.10. Note that the energy use is affected slightly by the change in control strategy even when no demand response is extant, as shown in Table 4.11. In the case of TOU, no demand response is achieved by using the fixed occupancy set point schedule. In the case of RTP and new thermostats no demand response is achieved by setting the comfort $K = \infty$.

Table 4.10: Residential energy cost with demand response inactive

	Fixed	**TOU**		**RTP**		**New**	
	($/month)	($/month)	(%)	($/month)	(%)	($/month)	(%)
Seattle winter	180.1	180.2	+0.0	180.1	−0.0	180.1	−0.0
Seattle summer	98.1	98.1	−0.0	98.2	+0.0	98.2	+0.0
Miami summer	144.8	144.8	+0.0	144.7	−0.0	144.7	−0.0
Phoenix summer	175.0	175.0	−0.0	175.0	−0.0	175.0	−0.0

Table 4.11: Residential energy use with demand response inactive

	Fixed	**TOU**		**RTP**		**New**	
	(kWh/day)	(kWh/day)	(%)	(kWh/day)	(%)	(kWh/day)	(%)
Seattle winter	79.4	79.4	0.0	79.5	+0.1	79.5	+0.1
Seattle summer	43.3	43.3	0.0	43.3	+0.1	43.3	+0.1
Miami summer	65.6	65.6	0.0	65.7	+0.1	65.7	+0.1
Phoenix summer	75.9	75.9	0.0	75.9	+0.1	75.9	+0.1

4.5 Performance Metrics

The individual houses are simulated in the four study cases for fixed prices, time-of-use prices with and without demand response, and real-time prices with and without demand response for both the transactive thermostat design and the new thermostat design. In the case of TOU homes, the response results from the change of set point from an occupancy schedule to a tariff schedule. In the case of the RTP homes the response results from the change from a 1°F deadband around each set point to the $\pm\Delta P/K$ comfort set point offset from the heating or cooling set points, where ΔP is the normalized price differential $(P_C - P_A)/P_D$.

The following performance data are collected for analysis. Data is not collected from the experiment homes when the results are the same as the baseline fixed price home.

Design: (1 season sampling interval) effective building heat transfer coefficient, floor area, envelope heat transfer coefficient, air heat capacity, mass heat transfer coefficient, mass heat capacity, design heating capacity, design cooling capacity, heating design temperature, cooling design temperature.

End-uses: (1 hour sampling interval) system, lights, plugs, dishwasher, microwave, freezer, refrigerator, range, clotheswasher, dryer.

Meter: (5 minute sampling interval) energy interval meter, prevailing price, monthly bill accumulator.

House: (1 minute sampling interval) Outdoor air temperature, indoor air temperature, heating set point, cooling set point, occupancy, system mode

Using the data collected, the following performance data are computed for analysis.

Energy use: Average daily energy use is obtained from the meter at 1 hour intervals for houses on fixed and TOU tariffs and at 5 minute intervals for houses on RTP tariffs.

Cost: Monthly cost is calculated by summing energy use interval metering and multiplying by the prevailing price for the interval. The billing period ends on the last day of the month at 23:59:59.

Temperature error: The mean temperature set point error is obtained by computing the mean of the difference between the indoor air temperature and the prevailing set point, e.g., heating in winter and cooling in summer.

Temperature deviation: The mean temperature deviation is obtained by computing the mean of the square difference between the indoor air temperature and the prevailing set point, e.g., heating in the winter and cooling in summer.

Discomfort degree-hours: The discomfort degree hours for cooling and heating are obtained by computing the time-integral of indoor air temperature above (cooling)

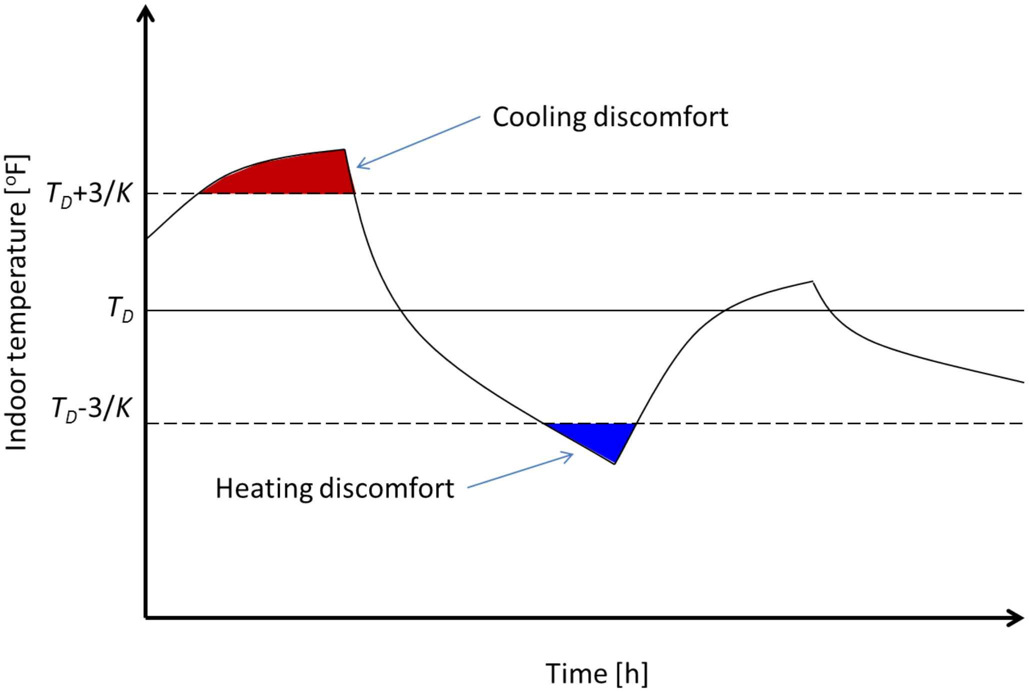


Figure 4.5: Cooling and heating discomfort degree-hours

and below (heating) the maximum and minimum allowable temperatures. In the case of the fixed and TOU homes this range is $T_C + \frac{1}{2}D$ and $T_H - \frac{1}{2}D$, respectively. For the RTP and new thermostat homes it is $T_C + 3/K$ and $T_H - 3/K$, respectively. This metric is illustrated in Figure 4.5.

4.6 Summary of Experiment Design

Table 4.12 summarizes the experiment model features used in evaluating the performance of the new thermostat design.

Table 4.12: Summary of Experiment Model Features

	Fixed	**TOU**	**RTP**	**New**
Thermal Response				
1st-order response	Y	Y	Y	Y
2nd-order response	Y	Y	Y	Y
3rd-order response	N	N	N	N
Delay response	N	N	N	N
Heat Pump				
Heating	Y	Y	Y	Y
Cooling	Y	Y	Y	Y
Auxiliary	Y	Y	Y	Y
Emergency	N	N	N	N
Defrost	N	N	N	N
Reversing lockout	N	N	N	N
Controller				
One speed fan	Y	Y	Y	Y
Two speed fan	N	N	N	N
Variable speed fan	N	N	N	N
Proportional fan control	N	N	N	N
Thermostat deadband (°F)	1.0	1.0	1.0	0.0 (1)
Refractory time (min)	2	2	2	5
Set points	2	2	2	2
Setback (°F)	–	2(2)	–	–
Occupancy modes	3	3(2)	3(3)	3(3)
Comfort setting (p.u.)	–	–	1.0	1.0
Price signal	N	2-tier(2)	5 min	5 min

Notes:

(1) Deadband is disabled.

(2) Setback schedule follows TOU price schedule with DR.

(3) Occupancy mode controls both set point and comfort.

Chapter 5

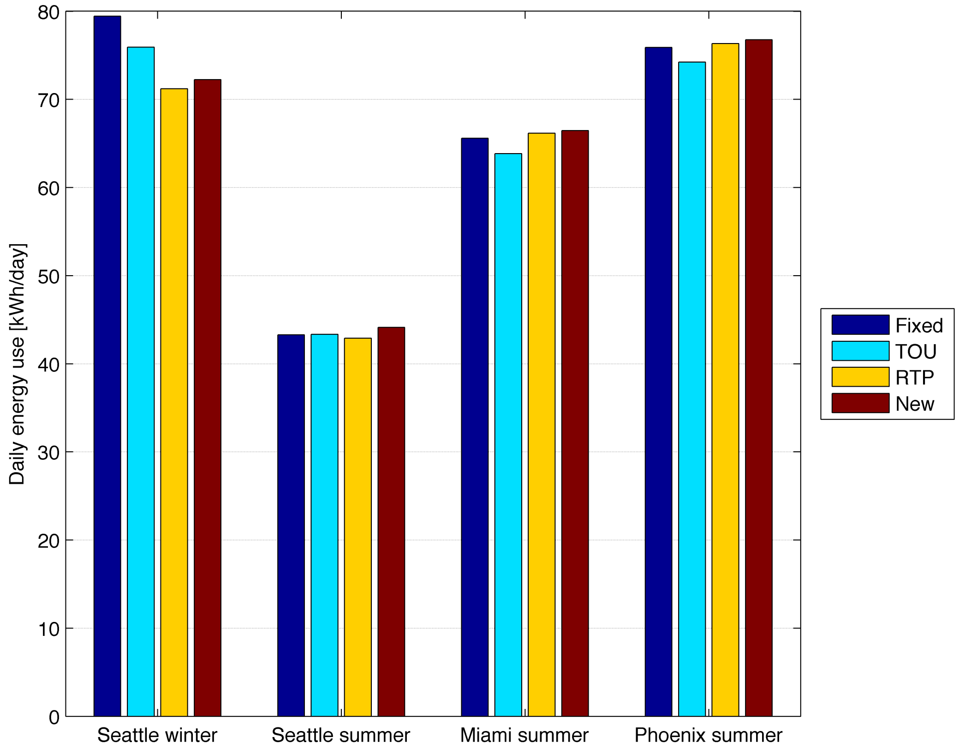
Evaluation of New Thermostat

This chapter describes the analysis method and results obtained for the performance of the new thermostat control design when compared to that of conventional fixed and time-of-use (TOU) pricing setback schedules, as well as the transactive thermostat used for the Olympic and Columbus real-time pricing (RTP). The energy, comfort, and economic impacts are summarized and discussed to determine whether the new thermostat performs well enough to be accepted by consumers and utilities and with a view to identifying the open issues and opportunities for future research.

5.1 Energy Use Impacts

The performance evaluation simulations are run with nominal demand response, i.e., for TOU a 2°F setback schedule that coincides with the tariff schedule, and for RTP comfort gain settings for night, home, and away of $K = 1.0$, 1.5, and 0.5, respectively.

The energy use impacts are shown in Figure 5.1. The TOU demand response shows a reduction in energy consistent with customers who change their thermostats from the unresponsive occupancy-driven set point schedules to responsive tariff-driven set point schedules. These results are consistent with those of other studies of TOU



	Fixed	**TOU**		**RTP**		**New**	
	(kWh/day)	(kWh/day)	(%)	(kWh/day)	(%)	(kWh/day)	(%)
Seattle winter	79.4	75.9	−4.4	71.2	−10.3	72.2	−9.1
Seattle summer	43.3	43.3	+0.1	42.9	−0.9	44.1	+2.0
Miami summer	65.6	63.8	−2.7	66.2	+0.9	66.5	+1.3
Phoenix summer	75.9	74.2	−2.2	76.3	+0.6	76.8	+1.2

Figure 5.1: Total home energy use with demand response active

demand response [31].

The RTP results for heating shows a very significant energy use reduction but cooling results are mixed and modest in comparison. It should be noted that increases in energy consumption were also observed in the Olympic and Columbus results, although the magnitude of the increase was much greater in the Olympic results because of an error in the auxiliary heating control.

In the Olympic study an increase in energy of about 16% was observed for heating conditions [5]. This increase is believed to be caused by the unnecessary use of auxiliary heating during thermostat set-up events in excess of 2°F. To date there has been no attempt to rigorously study what the Olympic results would have been had the auxiliary heating control not be misapplied. It should be noted that this thesis has completely corrected the auxiliary control problem only in the RTP and new thermostat, and the auxiliary heating can be engaged during thermostat set-up in the winter. In any case this result may provide initial evidence of what the Olympic study would have yielded had the auxiliary heating control been implemented correctly then.

The Columbus study also found increases in energy use in cooling conditions of about 1% when congestion pricing was extant. Decreases of about 5% were observed when congestion pricing was not in effect [6]. Because congestion pricing typically expressed itself in short-term price volatility, the summer results are consistent with the observations from the Columbus study.

In general the heating energy use impacts of the new thermostat are similar to those of the RTP thermostat. However, the cooling energy use impacts of the new thermostat are approximately double those of the RTP thermostat. It is not clear exactly what is the root cause of this increase, but it is possibly related to so-called "round-trip" efficiency considerations that result from the use of thermal storage as a proxy for electric energy storage [68]. These round-trip efficiency impacts may be increased by the minimum 5-minute runtime under the new thermostat, which preferentially increases the amount of thermal storage being used for short-term events with respect to long-term events.

Table 5.1: Heating and cooling relative set point errors

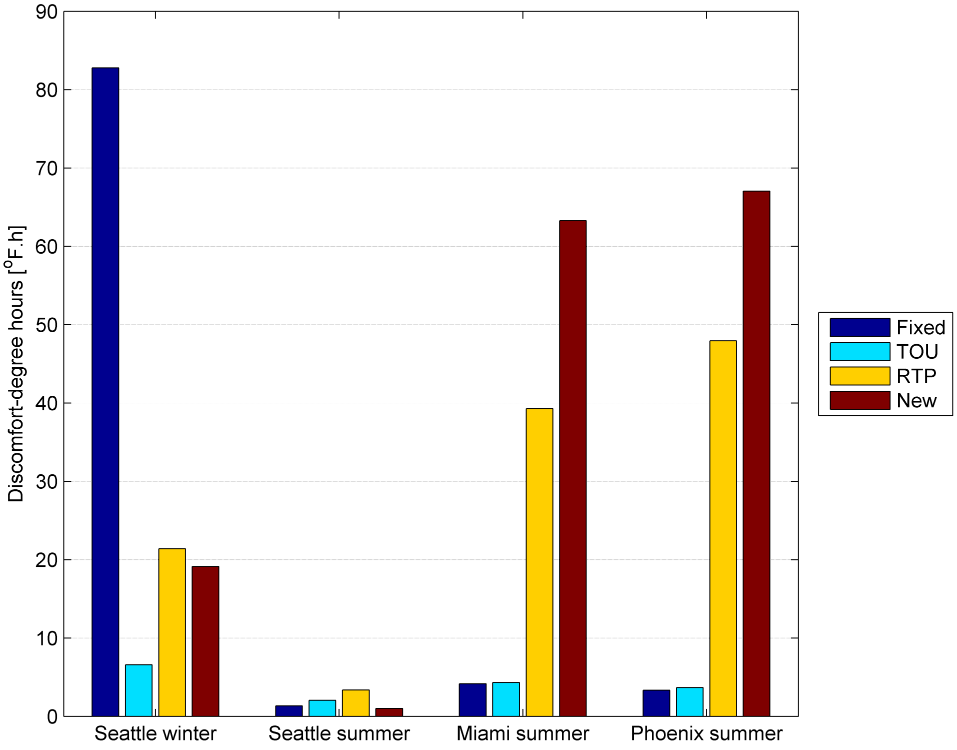
	Heating				**Cooling**			
	Fixed (%)	**TOU** (%)	**RTP** (%)	**New** (%)	**Fixed** (%)	**TOU** (%)	**RTP** (%)	**New** (%)
Seattle winter	6.0	1.2	0.4	0.2	0.0	0.0	0.0	0.0
Seattle summer	0.5	< 0.1	0.2	0.3	0.3	0.3	0.0	0.0
Miami summer	0.0	0.0	0.0	0.0	0.7	0.9	< 0.1	0.2
Phoenix summer	0.0	0.0	0.0	0.0	0.8	1.1	0.2	0.3

5.2 Comfort Impacts

The consumer comfort impacts are examined using two performance metrics. The heating/cooling relative set point errors are computed as the standard deviation of the air temperature with respect to the prevailing set point. The fixed and TOU set point errors are computed with respect to the deadband of $D = 1°\text{F}$, so only air temperatures observed outside $\pm\frac{1}{2}°\text{F}$ are considered. Such errors occur each time the set point is changed either from a change in occupancy schedule or price change, which explains why the set point errors are relatively high for both fixed and TOU controls.

The RTP and new thermostat control set point errors shown in Figure **??** account for the comfort setting K and thus allow for larger fluctuations of the indoor air temperature, provided it does not go outside the consumer's $\pm 3K°\text{F}$ comfort band. Because the price signal is generated from a Gaussian distribution, we expect the RTP signal to deviate by more than 3σ less than 1% of the time. The new thermostat can deviate more because of the increased probability of indoor air temperature overshoot. Nonetheless Table 5.1 indicates such a deviation occurs less than 1% of the time with the new thermostat.

We also apply a more sensitive evaluation of the comfort performance using the discomfort degree hour method for deviations in excess of 1°F, as shown in Figure 5.2. The results suggest that while the new thermostat is slightly less able to maintain the



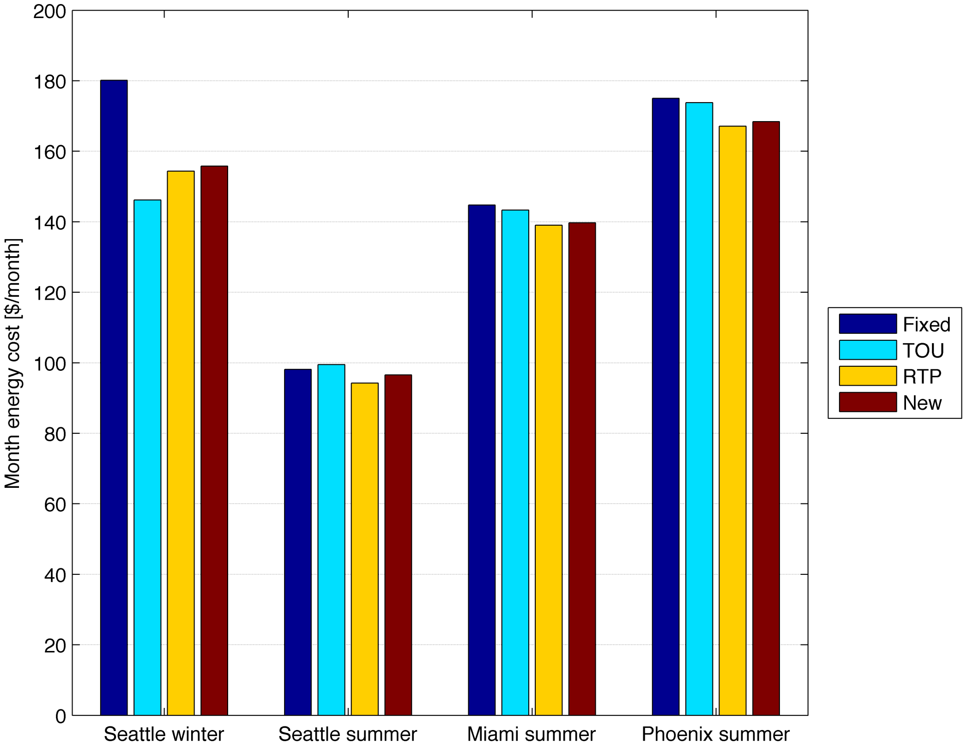
	Fixed (°F.h)	**TOU** (°F.h)	**RTP** (°F.h)	**New** (°F.h)
Seattle winter	83	7	21	19
Seattle summer	1	2	3	1
Miami summer	4	4	39	63
Phoenix summer	3	4	48	67

Figure 5.2: Heating and cooling discomfort degree hours for 1°F deviations

consumer's preferred comfort, it is very nearly as good as the RTP thermostat and better than the conventional fixed thermostat with a setback schedule.

5.3 Economic Impacts

The utility revenue impacts, which is also the consumer cost impacts of the TOU, RTP and new thermostat demand responses are shown in Figure 5.3. In this analysis we will



	Fixed	**TOU**		**RTP**		**New**	
	($/month)	($/month)	(%)	($/month)	(%)	($/month)	(%)
Seattle winter	180.1	146.2	−18.8	154.4	−14.3	155.8	−13.5
Seattle summer	98.1	99.5	+1.3	94.3	−4.0	96.6	−1.6
Miami summer	144.8	143.3	−1.0	139.0	−4.0	139.7	−3.5
Phoenix summer	175.0	173.8	−0.7	167.1	−4.5	168.4	−3.8

Figure 5.3: Energy cost with demand response active

consider the consumer's budget as equivalent to what is denoted "income" in the sense that is used in the consumer theory of microeconomics, i.e., it is the invariant amount of the consumer's money allocated to comfort obtained from electricity consumption. Other consumer goods are not considered, and in this context only the consumer's allocation of money to off-peak versus on-peak electricity is examined. This way "revenue neutral" for the utility is equivalent to a constant consumer budget and the revenue neutrality tariff design corresponds to designing a tariff the satisfies a

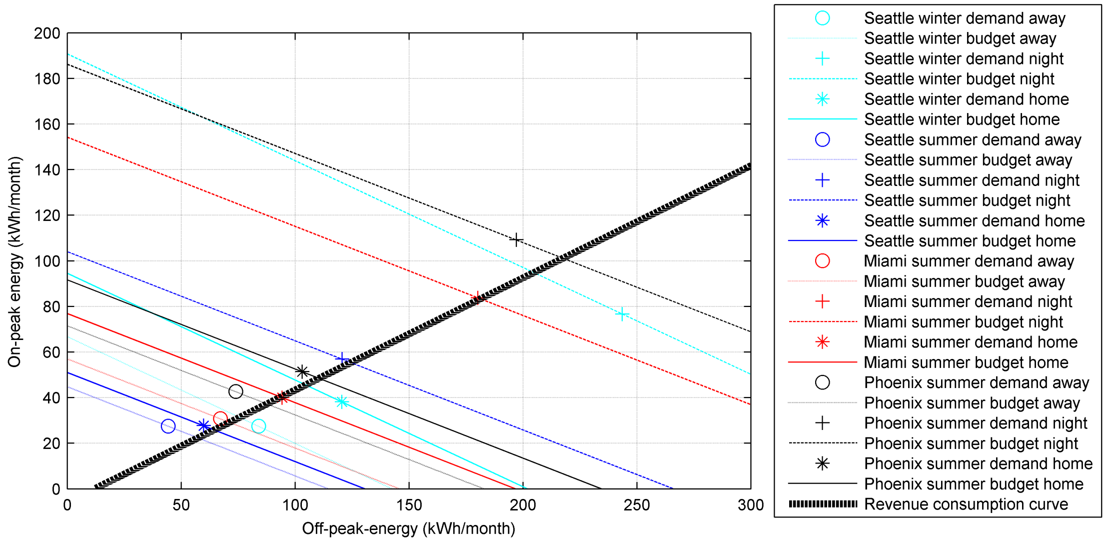


Figure 5.4: Time-of-use demand, revenue neutral and revenue expansion paths

consumer's constant budget constraint in the absence of demand response.

The responsive thermostat designs all give rise to demand elasticity that can be estimated from the simulation, with the understanding that this elasticity is primarily driven by the choices of setback temperatures in the case of TOU customers and the choices of occupancy-based comfort settings in the case of the RTP customers. In either case we estimate the demand elasticity by computing the ratio of the fractional change in energy use $\Delta E/E$ to a fractional change in energy price $\Delta P/P$, or

$$\eta = \frac{P}{E}\frac{\Delta E}{\Delta P} \tag{5.1}$$

TOU energy demand elasticity is estimated separately for off-peak and on-peak conditions with respect to each of the customer's occupancy modes under fixed pricing (i.e., home, away, night), as shown in Figure 5.4. Energy demands are plotted with the revenue neutral lines for that occupancy mode. The consumer's indifference curves (not shown) are neither perfect substitutes nor perfect complements, but they are expected to be convex toward the origin, i.e., Cobb-Douglas [42]. The demands shown are the consumer's optimal choices where the budget lines are tangent to those curves. The resulting revenue expansion path is analogous to an income consumption curve for a representative customer because the budget curves are equivalent to revenue neutrality in this context. For TOU demand response the revenue expansion path is positive indicating that TOU energy is indeed a normal good and the indifference curves are therefore convex. Because no corner solutions for on-peak/off-peak consumption were found and in fact there is no reason to believe that TOU off-peak energy is a perfect complement to on-peak energy, the indifference curves are thus strictly convex toward the origin.

In general negative values of elasticity are expected because the change of energy use should have an inverse relation to the price. However, the fixed price occupancy schedule causes large set-back and set-up changes in energy demand that give rise to large fluctuations in the elasticity of demand for TOU response. The transition periods are when the greatest amount of inter-temporal substitution is taking place and this effect confounds the calculation of demand elasticity, as observed in Table 5.2.

In some cases the change in schedule confers a relatively large benefit when the TOU set point schedule is adopted, this results in very large elasticities, while in other cases a very large penalty is incurred. As a result the total energy consumption changes for various combinations of occupancy and tariff schedules can vary significantly based on the sign and magnitude of the substitution across the occupancy or tariff boundary. This gives rise to high sensitivity of demand elasticity with respect to the consumer choices of temperature set points and occupancy schedule. The high sensitivity of observed demand elasticity for TOU demand response is what makes the problem of optimal TOU tariff design so challenging for utilities and regulators and is in large part the rationale for seeking tariffs that allow consumers to observe real-time prices

Table 5.2: TOU demand elasticity

City	**Energy use** **Fixed** (kWh)	 **TOU** (kWh)	**Demand Elasticity** (pu)
Seattle winter elasticity			
of Off-peak demand			
with respect to Away occupancy	67	84	-0.57
with respect to Night occupancy	186	244	-0.66
with respect to Home occupancy	93	121	-0.66
of On-peak demand			
with respect to Away occupancy	51	27	-1.70
with respect to Night occupancy	148	77	-1.82
with respect to Home occupancy	73	38	-1.80
Seattle summer elasticity			
of Off-peak demand			
with respect to Away occupancy	46	44	0.07
with respect to Night occupancy	123	121	0.05
with respect to Home occupancy	60	60	-0.01
of On-peak demand			
with respect to Away occupancy	27	28	0.07
with respect to Night occupancy	55	57	0.07
with respect to Home occupancy	27	28	0.08
Miami summer elasticity			
of Off-peak demand			
with respect to Away occupancy	71	67	0.15
with respect to Night occupancy	190	180	0.14
with respect to Home occupancy	99	94	0.12
of On-peak demand			
with respect to Away occupancy	30	31	0.06
with respect to Night occupancy	82	84	0.05
with respect to Home occupancy	39	40	0.05
Phoenix summer elasticity			
of Off-peak demand			
with respect to Away occupancy	78	74	0.12
with respect to Night occupancy	206	197	0.11
with respect to Home occupancy	107	103	0.10
of On-peak demand			
with respect to Away occupancy	42	43	0.05
with respect to Night occupancy	107	109	0.04
with respect to Home occupancy	50	51	0.04

[69]. In any case the absence of reports describing failed TOU tariffs is certainly not evidence that TOU tariffs necessarily work—selective publication of tariff design can lead to a bias toward reporting of TOU tariffs that work, with exceptions noted [70].

The defects of the TOU tariff design could be remedied by producing separate tariffs for each city and/or season. However, it is the objective of this thesis to make the TOU controller technical performance comparable to those of the RTP and new thermostat, so resolving economic deficiencies of the TOU tariff design itself is not in the scope of this thesis and the tariff design is not corrected to eliminate this problem.

Unfortunately there is no accepted method for performing the demand elasticity analysis for RTP results and thus neither for the new thermostat. We can only compute the aggregate demand elasticity and the elasticities of the night, home, and away occupancies, as shown in Table 5.3. The demand elasticity of the new thermostat is very close to that of the RTP thermostat while both consistently perform better than the TOU thermostat, to the extent that one can compare these to the TOU elasticity results (see Table 5.2). Certainly the RTP and new elasticities are more consistent with previous studies and more stable than those for TOU across the various occupancy modes.

The results also suggest that certain occupancy modes are indeed sufficiently elastic to justify deployment of RTP systems to mitigate on-peak demand. It is interesting to note that “away” (weekdays only) in the summer is highly elastic as expected, but home is more elastic than night. This is very likely due to the fact the night setback in the conventional fixed tariff thermostat is already quite energy efficient and there is little opportunity for additional savings, while there are still some savings to be realized in the daytime on weekends. This observation suggests that the new thermostat may present better elasticity characteristics than expected during summer peak cooling conditions.

Table 5.3: RTP demand elasticity

City	**TOU** (pu)	**RTP** (pu)	**New** (pu)
Seattle winter elasticity of			
Aggregate demand	-0.28	-2.41	-1.90
Night demand	0.76	0.19	0.20
Home demand	4.42	-0.23	-0.23
Away demand	0.91	0.32	0.32
Seattle summer elasticity of			
Aggregate demand	-0.12	-0.27	0.54
Night demand	0.41	0.25	0.24
Home demand	0.86	-0.16	-0.17
Away demand	-0.77	-0.19	-0.18
Miami summer elasticity of			
Aggregate demand	1.55	0.17	0.27
Night demand	-0.77	0.23	0.22
Home demand	0.01	-0.07	-0.06
Away demand	-1.72	-0.26	-0.25
Phoenix summer elasticity of			
Aggregate demand	1.48	0.11	0.23
Night demand	-0.54	0.24	0.23
Home demand	0.04	-0.09	-0.08
Away demand	-1.73	-0.27	-0.24

5.4 Feeder Load Control Impacts

A feeder-scale simulation of 100 homes in Phoenix is used to illustrate the open-loop response of the load to changes in the price signal. A sample of the output is shown in Figure 5.5. The result clearly illustrates how the new thermostat (blue) remedies the RTP thermostat drift problem (red) as they respond to the price signals (black). Note that the feeder load control is simulated as an open-loop control and the demand response gain K is not influenced by the states of loads prior to clearing the market.

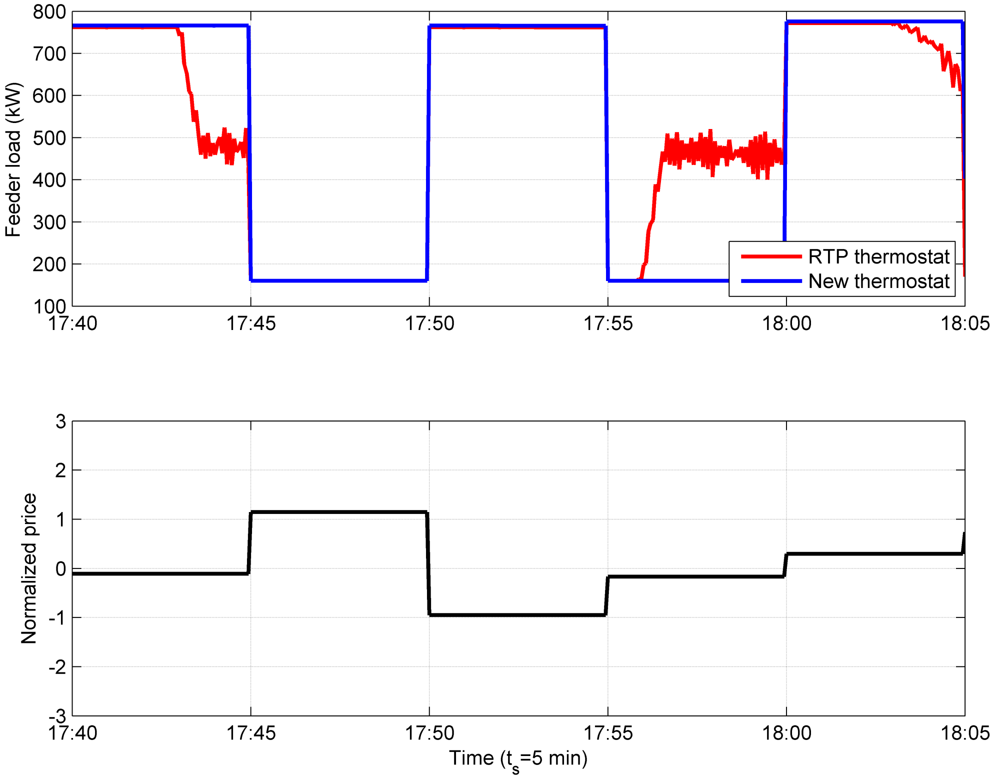


Figure 5.5: Feeder open-loop load control response to price

5.5 Open Issues and Opportunities

In the conduct of the experiment and analysis of the new thermostat design a number of issues were identified that, if addressed, would allow a systematic estimation of impacts and benefits of this and future designs for thermostatic controls.

Occupancy Schedules: The fixed tariff customer's baseline occupancy has a significant impact of the benefits analysis of various alternative rates. TOU customers typically alter their thermostat's occupancy schedule to match the tariff schedule. In response to these changes in schedule TOU customers also change the set points such that they maintain the desired comfort. This mixed temporal and thermal response is very challenging to analyze unless the responses can be separated. At the present time there is no analytic method for separating these two responses. Consequently it can be difficult to obtain clear and distinct load-shifting and load-curtailment performance results when occupancy schedules are altered by the consumer.

Lack of suitable economic analysis methods: At present the economic analysis of TOU rate is very challenging [71]. In this thesis only a simplistic analysis of demand elasticity was performed. Other methods for studying TOU rates exist but they can be very difficult to implement [72] and were not attempted in this analysis. The challenge for RTP rates is even more serious because there are no generally accepted methods yet for determining the short-term demand elasticity of consumers under real-time tariffs. However, the development of linear time-invariant load control designs by utilities may allow the identification of relatively simple transfer functions from price to energy that permit the derivation of analytic forms for the demand elasticity of load in the aggregate in both time domain and frequency domain.

The design and analysis of this new thermostat has revealed a number of potential valuable avenues for future research in transactive control system design.

Mass temperature control: The design of fast-acting demand response using a building's air heat capacity revealed the opportunity to separately construct a system for observing and controlling the building thermal mass. This slow-acting demand response can be used to "position" buildings to respond better to long-term fluctuations in energy prices arising from existing forward energy markets independently from the short-term fluctuations that would arise from ancillary service markets when they become more prevalent.

Split tariffs: There is no economic justification for requiring consumers to place both technology-response loads and behavior-response loads on the same tariff. Split tariffs should be considered wherein the technology-driven responsive loads (e.g., thermostatic loads) are sent fast-changing prices (e.g., RTP) while behavior-driven responsive loads are subject to regular time-of-use prices that are known to influence consumer habits. Meanwhile, unresponsive loads can continue to be charged fixed prices that encourage energy conservation.

5.6 Summary of Results

The principal result of this thesis is the design of a transactive thermostat for residential space heating/cooling that resolves the short-term load control drift problem found in existing real-time price responsive thermostats. The new control system can be modeled as a linear time-invariant system for short-term changes to real-time prices. This is an important innovation because it enables the design of utility load control systems that are themselves modeled as linear time-invariant systems for short-term real-time price response and thus subject to design and integration with existing control systems using classical control theory. This can dramatically increase the short-term rate of adoption of transactive control systems by making them much more approachable to power system engineers who haven't been trained or aren't comfortable working with highly non-linear or distributed control systems.

The technical analysis shows that the comfort impacts on the consumer are consistent with those of the RTP thermostat and within the comfort control specifications of the consumer, even as occupancy changes. In addition, the energy consumption and cost savings opportunities for the consumer are consistent with those of the RTP thermostat. Thus the new thermostat can be expected to offer roughly the same overall energy and cost performance as the RTP thermostat did in the Olympic and

Columbus studies, while correcting the known deficiencies observed in those studies.

The economic analysis of the new thermostat shows that like the RTP thermostat, the demand elasticity is much more consistent and predictable than TOU demand response provides. TOU performance is very sensitive to consumer choices in set point schedules, a process that consumers find very challenging to follow and thus is not likely to result in a setup that reflects the consumers true preferences. In contrast, RTP and the new thermostat's performance is sensitive primarily to the consumer's comfort setting, which is much simpler to understand and set, and thus is much more likely reflect consumers' true preferences. However, under certain conditions, the new thermostat, like the RTP thermostat still has positive demand elasticity, meaning the energy use is sometime proportional to price rather than inversely proportional to price. This condition appears to be limited off-peak hours and may suggest that RTP energy consumption may not be a strictly normal good under certain conditions when compared to fixed price energy consumption.

Finally, a modeling and analysis framework for the study and design of residential thermostatic device controls has been constructed and validated for this thesis. This framework can be expanded upon to study the behavior of thermostatic appliances and to study the effect of feedback control of demand response when deployed by a utility.

Chapter 6

Conclusions

This thesis examined the behavior of a new control strategy for residential heating and cooling thermostats based on the transactive control system design. The new thermostat outperforms conventional thermostats in providing demand response and does so in a manner that is highly conducive to aggregate load control by utilities using real-time price signals. The new thermostat has all the features and advantages of real-time price (RTP) and time-of-use (TOU) thermostats and overcomes disadvantages typically associated with them. In particular, the main features of this new thermostat are:

No Aggregate Load Drift: The new thermostat eliminates the hysteresis arising from the deadband in the Schmitt trigger control element used in conventional, TOU and RTP thermostats. As a result the new thermostat does not exhibit an aggregate load drift behavior between price clearing events in the market.

Consumer Comfort Control: The new thermostat maintains satisfactory control of indoor air temperature. The new thermostat enhances the favorable economic and thermal control characteristics of conventional, TOU and RTP thermostats. Most significant is the new thermostat allows consumers to specify a comfort preference for each occupancy mode, e.g., home/awake, night/sleep, away/work, and by extension any others the consumer might add.

Load shifting and Cost Savings: The new thermostat provides the desired energy shifting and cost savings properties also found in the RTP thermostats and enhances those found in the conventional and TOU thermostat, especially in the short-term response time intervals. In particular, the new thermostat's summer air-conditioning demand elasticity for the entire residential load is in the range of 6% to 25% for occupancy modes in cities summer demand response is a resource. Larger total house demand elasticities could be achieved if a similar control strategy were adopted for other thermostatic end-use load such refrigerators, freezers, water heaters, dish washers, clothes washers, and dryers.

Transactive Control Compatibility: The new thermostat demand response implementation is consistent and compatible with the RTP thermostat demand response design used in the Olympic and Columbus transactive control studies. Thus it can operate in real-time distribution capacity auction system and provides all the benefits associated with transactive systems.

From the consumer's perspective the new thermostatic control design's performance compares favorably to conventional, TOU thermostats, and RTP thermostat. In particular the new thermostat exhibits the following characteristics that appeal to consumers.

Control: The new thermostat offers far better control of fast-acting demand response than conventional and TOU thermostats and the same degree of control over short-term comfort as a function of electricity price that the RTP thermostat offers. Consumers can indicate a comfort preference for each occupancy mode and the new thermostat uses that comfort setting to regulate energy use and significantly reduce heating/cooling costs.

Savings: The new thermostat significantly reduces cost relative to conventional and TOU thermostats, consistent with those for RTP thermostats, and significantly improves on the heating energy use and overall cost performance of demand response using conventional and TOU thermostats.

From the utility's perspective the new thermostat offers one very significant advantage over the other demand response thermostat designs. The new thermostat provides significantly better control tracking of the load for the price given. In particular, the heating/cooling load under control of the new thermostat will remain at the level associated with the price given for the entire duration of the pricing time-interval. Unlike conventional, TOU and RTP thermostats, which allows the heating/cooling system load to change when the deadband is exceeded, the new thermostat maintains the system load as dispatched until the new price is received. Thus the impact of the error is shifted from the utility where it cannot be mitigated without resorting to more complex bid/response compensation/anticipation strategies to the consumer where its impact can be mitigated by the consumer's comfort setting.

The economic impacts of the new thermostat design remain clouded by the lack of methods for rigorously analyzing real-time price-based demand response. This gap in our engineering and economic analysis methods remains an important problem that has yet to be fully overcome. In particular, we are unable precisely determine the microeconomic performance of the new thermostat control systems. The inability to precisely quantify instantaneous demand elasticity of real-time price demand response systems will continue to hamper the deployment of control strategies that employ them by making it difficult to anticipate the economic impact of their adoption. Utilities will continue to seek methods that will enhance their ability to minimize their costs in the face of demand response, especially as they are forced to respond to growth in the availability and flexibility of distributed renewable and storage resources.

6.1 Main Contributions

This thesis has demonstrated the following important contributions to the development of transactive systems.

1. A new thermostat design now exists that enables reliable and predictable aggregate demand response resources and makes them available to utilities for short-duration fast-acting reliability services. This thermostat design overcomes the concerns that utilities have with real-time price-based demand response, particularly in resource planning when they have the greatest financial impact and in system operation when they have the greatest technical impact.

2. A comprehensive set of performance metrics for demand response control using thermostatic devices has been developed and implemented using GridLAB-D, a scalable open-source smart-grid analysis tool. These metrics give utilities the ability to rigorously design, monitor, and optimize the performance of aggregate demand response control systems. Consequently utilities will be able to consistently provide more reliability services based on demand response to bulk system operators and derive economic benefits that can be passed on to the consumers who provide the underlying load resources.

3. An economically and technically robust design for residential HVAC equipment controls is now available that supports aggregate demand response. This gives consumers the ability to better control when and to what degree their space conditioning systems are participating in demand response services provided by the utility to the bulk system operators.

6.2 Recommendations

The following avenues of research are recommended based on the results obtained in this thesis.

1. *Develop a method for separately characterizing inter-period (long-term load-shifting) demand response from the intra-period (short-term load-shedding) demand response.* The fact that both kinds of demand response exist is well-known. However there is no rigorous method extant for identifying which part of the total demand response observed arises from load-shifting behavior and which is from load-shedding. In addition these are expected to be independent and thus separate to a first-order. However almost all loads add heat to the indoor air and thus can both affect and be affected by each other to a potentially significant degree. This seriously complicates the matter and has limited the development of methods to resolve the question.

2. *Develop a method to quantify the economic performance of real-time price-based demand response.* The existence of linear time-invariant aggregate load control models at the utility operations level permits the derivation of transfer functions for energy response to price. These transfer functions can be used to obtain analytic forms of demand elasticity for the short-term response in both time domain and frequency domain.

3. *Develop an aggregate load control system for utilities to deploy on existing transactive demand response systems.* The use of linear time-invariant thermostats will give rise to linear aggregate demand response control systems that can be subject to standard feedback control design methods. These linear closed-loop load control designs may allow utilities to mitigate the stability, observability

and controllability concerns that have been raised with open-loop load control strategies [73].

4. *Design a slow demand response thermostat control strategy for second-order thermal systems.* The design of fast-acting demand response using a building's air heat capacity revealed an opportunity to separately construct a system for observing and controlling building thermal mass. This slow-acting demand response can be used to position buildings to respond better to long-term fluctuations in energy prices arising from existing forward energy markets independently from the short-term fluctuations that would arise from ancillary service markets when they become more prevalent. A critical element of this approach will be to establish observability of the second state variable, e.g., the thermal mass temperature. This can be done either by direct measurement of the mass temperature or estimating it from the derivative of the air temperature, provided an appropriate adaptive band-limited differentiator can be designed.

5. *Design and test a tariff structure that allows technical response loads to be billed separately from human response loads.* There is no economic justification for forcing consumers to place both technology-response and behavior-response loads on the price structure. Split tariffs should be considered when the technology-driven responsive loads are available while behavior-driven responsive loads are subject to regular time-of-use prices that can influence long-term consumer habits.

6. *Automate the tariff design mechanism in GridLAB-D.* Analysis of designs such as the one studied in this thesis require a very time-consuming revenue neutral tariff design process. The manual method used in this thesis limited the ability to use tariffs that were well-designed for the study cities and seasons and limited

the number of studies that could reasonably be tested. Development of an automated tariff design module in GridLAB-D will significantly augment the analysis capabilities of GridLAB-D by allowed very wide-ranging scenarios to be explored very quickly.

Appendix A

Tables in SI Units

Table 4.1: Cities and climate conditions

City	**TMY File**	**Timezone**	**Low**	**High**	**Solar**
			(°C)	(°C)	(W/m^2)
Seattle	WA-Seattle.tmy2	PST+8PDT	-5	37	1028
Phoenix	AZ-Phoenix.tmy2	MST+7	-3	46	1072
Miami	FL-Miami.tmy2	EST+5EDT	3	34	1042

Table 4.2: IECC end-use energy for model home in study cities

End-use	**Seattle**		**Miami**		**Phoenix**	
	(MWh/y)	(%)	(MWh/y)	(%)	(MWh/y)	(%)
Heating	3.4	19	0.2	1	0.9	4
Cooling	0.8	5	6.1	32	6.3	31
Fans	1.0	5	1.5	8	1.9	9
Hotwater	4.0	22	2.2	12	2.3	11
Lighting	1.4	8	1.4	7	1.4	7
Plugs	7.7	42	7.7	40	7.7	37
Total	18.4	100	19.2	100	20.6	100

Table 4.3: House design

Parameter	**Seattle**	**Miami**	**Phoenix**
Floor area (m^2)	223	223	223
U_A (W/°C)	283	227	227
C_A (kJ/°C)	1931	1735	1735
U_M (W/°C)	5884	5884	5884
C_M (kJ/°C)	7828	7033	7033

Table 4.5: Occupancy and thermostat setpoint schedule

Occupancy	**Weekday**	**Weekend**	**Heating** (°C)	**Cooling** (°C)	**Comfort** ($/°C)
Night	20:00−6:00	23:00−7:00	20	24	0.56
Home	6:00−8:00,18:00−22:00	7:00−23:00	22	26	0.83
Away	8:00−18:00	–	19	27	0.28
Vacation	–	–	–	–	–

Table 4.6: Heatpump design criteria and capacities for study cities

Parameter	**Seattle**	**Miami**	**Phoenix**
T_H (°C)	-5	3	-3
T_C (°C)	37	34	46
Q_H (kW)	18	16	19
Q_C (kW)	18	16	19

Appendix B

Simulation Models

B.1 Common Models

B.1.1 Demand Response Controllers

```
// DR enabled house
module residential;
class house {
    double k; // demand responsiveness factor
    double occupancy; // scheduled occupancy
}
module powerflow;
class triplex_meter {
    double occupancy; // schedule occupancy
}

// Olympic/Columbus RTP thermostat
class rtp_thermostat {
        object market;
    double P;
    double Pavg;
    double Pstd;
    double k;
    double dlc_offset;
    double Tout;
    double Tair;
    double Theat;
    double Tcool;
    double Taux;
    double dTair;
    double dTairMin;
    int64 mode;
    timestamp t_last; // time of last mode
    int64 m_last; // last mode
        intrinsic presync(TIMESTAMP t0, TIMESTAMP t1)
        {
                // retail price
                gl_get_value((OBJECT*)market,”price”,P);
                gl_get_value((OBJECT*)market,”price_mean”,Pavg);
                gl_get_value((OBJECT*)market,”price_stdev”,Pstd);

                // comfort setting and temperature offset
                gl_get_value(my->parent,”k”,k);
                dlc_offset = k*(P-Pavg)/Pstd;

        // thermostat info
                gl_get_value(my->parent,”heating_setpoint”,Theat);
        gl_get_value(my->parent,”cooling_setpoint”,Tcool);
                gl_get_value(my->parent,”air_temperature”,Tair);
        gl_get_value(my->parent,”outdoor_temperature”,Tout);
                gl_get_value(my->parent,”dTair”,dTair);
        Taux = Theat - 3*k;

        typedef enum {SM_OFF=1, SM_HEAT=2, SM_AUX=3, SM_COOL=4} SYSTEMMODE;

```

```
        // disable house's internal thermostat
        typedef enum {SM_NONE=2} THERMOSTATCONTROL;
        THERMOSTATCONTROL *pThermostatControl = (THERMOSTATCONTROL*)gl_get_addr(my->parent,"thermostat_control");
        *pThermostatControl = SM_NONE;

        // compute new setpoints
        Theat -= dlc_offset;
        Tcool += dlc_offset;

        // determine mode
        switch ((SYSTEMMODE)mode) {
        case SM_OFF:
            if ( Tair<Theat && dTair<-dTairMin )
                mode = SM_HEAT;
            else if ( Tair>Tcool && dTair>dTairMin )
                mode = SM_COOL;
            break;
        case SM_HEAT:
            if ( Tair>Theat )
                mode = SM_OFF;
            else if ( dTair<0 )
                mode = SM_AUX;
            break;
        case SM_AUX:
            if ( Tair>Theat )
                mode = SM_OFF;
            break;
        case SM_COOL:
            if ( Tair<Tcool )
                mode = SM_OFF;
            break;
        default:
            mode = SM_OFF;
            break;
        }

        // send mode signal
        SYSTEMMODE *pSystemMode = (SYSTEMMODE*)gl_get_addr(my->parent,"system_mode");
        if ( pSystemMode==NULL )
            gl_error("unable to get house override");
        else
            *pSystemMode = (SYSTEMMODE)mode;

        // private logging

                return TS_NEVER;
    };
}

// New thermostat
class new_thermostat {
        object market;
    double P;
    double Pavg;
    double Pstd;
    double k;
    double dlc_offset;
    double Tout;
    double Tair;
    double Theat;
    double Tcool;
    double Taux;
    double dTair;
    double dTairMin;
    int64 mode;
    timestamp t_last; // time of last mode
    int64 m_last; // last mode
        intrinsic presync(TIMESTAMP t0, TIMESTAMP t1)
        {
                // next event time
                TIMESTAMP t2 = ((t1/300)+1)*300;

                // retail price
                gl_get_value((OBJECT*)market,"price",P);
                gl_get_value((OBJECT*)market,"price_mean",Pavg);
                gl_get_value((OBJECT*)market,"price_stdev",Pstd);

                // comfort setting and temperature offset
                gl_get_value(my->parent,"k",k);
                dlc_offset = k*(P-Pavg)/Pstd;

        // thermostat info
                gl_get_value(my->parent,"heating_setpoint",Theat);
        gl_get_value(my->parent,"cooling_setpoint",Tcool);
                gl_get_value(my->parent,"air_temperature",Tair);
        gl_get_value(my->parent,"outdoor_temperature",Tout);
                gl_get_value(my->parent,"dTair",dTair);
        Taux = Theat - 3*k;

```

```
                // update HVAC state
                if ( t1%300 == 0 ) // time to update
                {
            typedef enum {SM_OFF=1, SM_HEAT=2, SM_AUX=3, SM_COOL=4} SYSTEMMODE;

                        // disable house's internal thermostat
                        typedef enum {SM_NONE=2} THERMOSTATCONTROL;
                        THERMOSTATCONTROL *pThermostatControl = (THERMOSTATCONTROL*)gl_get_addr(my->parent,”thermos
                        *pThermostatControl = SM_NONE;

                        // compute new setpoints
                        Theat -= dlc_offset;
            Tcool += dlc_offset;

                        // determine mode
            switch ((SYSTEMMODE)mode) {
            case SM_OFF:
                if ( Tair<Theat && dTair<-dTairMin )
                    mode = SM_HEAT;
                else if ( Tair>Tcool && dTair>dTairMin )
                    mode = SM_COOL;
                break;
            case SM_HEAT:
                if ( Tair>Theat )
                    mode = SM_OFF;
                else if ( dTair<0 )
                    mode = SM_AUX;
                break;
            case SM_AUX:
                if ( Tair>Theat )
                    mode = SM_OFF;
                break;
            case SM_COOL:
                if ( Tair<Tcool )
                    mode = SM_OFF;
                break;
            default:
                mode = SM_OFF;
                break;
            }

            // send mode signal
            SYSTEMMODE *pSystemMode = (SYSTEMMODE*)gl_get_addr(my->parent,”system_mode”);
            if ( pSystemMode==NULL )
                                gl_error(”unable to get house override”);
                        else
                *pSystemMode = (SYSTEMMODE)mode;

            // private logging
                }

                return t2;
        };
}
```

B.1.2 Market Model

```
// market class
class market {
    randomvar price[$/kWh];
    double price_mean[$/kWh];
    double price_stdev[$/kWh];
}
```

B.1.3 Occupancy Schedules

```
// baseline heating and cooling setpoints (no response)
#define TH_NIGHT=68
#define TH_HOME=72
#define TH_AWAY=66
#define TC_NIGHT=76
#define TC_HOME=78
#define TC_AWAY=80

// TOU prices
#define WINTER_OFFPEAK_PRICE=0.0540
#define WINTER_ONPEAK_PRICE=0.1153
#define SUMMER_OFFPEAK_PRICE=0.0540
#define SUMMER_ONPEAK_PRICE=0.1381

// TOU heating and cooling setpoints (TOU response)
#define TH_OFFPEAK=72
#define TH_ONPEAK=70
#define TC_OFFPEAK=80
```

```
#define TC_ONPEAK=78

// RTP comfort setttings (RTP esponse)
#define K_NIGHT=1.00
#define K_HOME=0.67
#define K_AWAY=2.00

// fixed schedules
schedule occupancy {
    * 22-5 * * 1-5         1 # night weekday
    * 6-8,18-21 * * 1-5    2 # home weekday
    * 9-17 * * 1-5         3 # away weekday
    * 23-6 * * 6-0         1 # night weekend
    * 7-22 * * 6-0         2 # home weekend
}
schedule heating_setpoint {
    * 22-5 * * 1-5         ${TH_NIGHT} # night weekday
    * 6-8,18-21 * * 1-5    ${TH_HOME} # home weekday
    * 9-17 * * 1-5         ${TH_AWAY} # away weekday
    * 23-6 * * 6-0         ${TH_NIGHT} # night weekend
    * 7-22 * * 6-0         ${TH_HOME} # home weekend
}
schedule cooling_setpoint {
    * 22-5 * * 1-5         ${TC_NIGHT} # night weekday
    * 6-8,18-21 * * 1-5    ${TC_HOME} # home weekday
    * 9-17 * * 1-5         ${TC_AWAY} # away weekday
    * 23-6 * * 6-0         ${TC_NIGHT} # night weekend
    * 7-22 * * 6-0         ${TC_HOME} # home weekend
}

// TOU schedules
schedule tou_tariff {
    * 9-17,21-5 * 10-6 * ${WINTER_OFFPEAK_PRICE} # winter offpeak
    * 6-8,18-20 * 10-6 * ${WINTER_ONPEAK_PRICE} # winter onpeak
    * 21-14 * 7-9 *      ${SUMMER_OFFPEAK_PRICE} # summer offpeak
    * 15-20 * 7-9 *      ${SUMMER_ONPEAK_PRICE} # summer onpeak
}

schedule heating_setback {
    * 9-17,21-5 * 10-6 * ${TH_OFFPEAK} # winter offpeak
    * 6-8,18-20 * 10-6 * ${TH_ONPEAK} # winter onpeak
    * 21-14 * 7-9 *      ${TH_OFFPEAK} # summer offpeak
    * 15-20 * 7-9 *      ${TH_ONPEAK} # summer onpeak
}
schedule cooling_setback {
    * 9-17,21-5 * 10-6 * ${TC_OFFPEAK} # winter offpeak
    * 6-8,18-20 * 10-6 * ${TC_ONPEAK} # winter onpeak
    * 21-14 * 7-9 *      ${TC_OFFPEAK} # summer onpeak
    * 15-20 * 7-9 *      ${TC_ONPEAK} # summer offpeak
}

// RTP schedules
schedule comfort {
    * 22-5 * * 1-5         ${K_NIGHT} # night weekday
    * 6-8,18-21 * * 1-5    ${K_HOME} # home weekday
    * 9-17 * * 1-5         ${K_AWAY} # away weekday
    * 23-6 * * 6-0         ${K_NIGHT} # night weekend
    * 7-22 * * 6-0         ${K_HOME} # home weekend
}
```

B.1.4 End-use Load Monitoring

```
// enduse_monitoring.h
//
// Header for enduse_monitoring class

#ifndef _ENDUSEMONITORING_H
#define _ENDUSEMONITORING_H

typedef enum {  BRK_OPEN=0,             ///< breaker open
                BRK_CLOSED=1,   ///< breaker closed
                BRK_FAULT=-1,   ///< breaker faulted
} BREAKERSTATUS; ///< breaker state
typedef enum {  X12=0,  ///< circuit from line 1 to line 2    (240V)
                X23=1,  ///< circuit from line 2 to line 3(N) (120V)
                X13=2,  ///< circuit from line 1 to line 3(N) (120V)
} CIRCUITTYPE; ///< circuit type

typedef struct s_circuit {
    CIRCUITTYPE type;   ///< circuit type
    struct s_enduse *pLoad;     ///< pointer to the load struct (ENDUSELOAD* in house_a, enduse* in house_e)
    complex *pV; ///< pointer to circuit voltage
    double max_amps; ///< maximum breaker amps
    int id; ///< circuit id
    BREAKERSTATUS status; ///< breaker status
    TIMESTAMP reclose; ///< time at which breaker is reclosed
```

```
    unsigned short tripsleft; ///< the number of trips left before breaker faults
    struct s_circuit *next; ///< next circuit in list
    // DPC: commented this out until the rest of house_e is updated
} CIRCUIT; ///< circuit definition

typedef struct s_panel {
    double max_amps; ///< maximum panel amps
    BREAKERSTATUS status; ///< panel breaker status
    TIMESTAMP reclose; ///< time at which breaker is reclosed
    CIRCUIT *circuits; ///< pointer to first circuit in circuit list
} PANEL;

#endif
```

```
// enduse_monitoring.glm
//
// Supports enduse monitoring by inspecting the house panel circuits

class enduse_monitor {
    char1024 filename;
    intrinsic create(object parent)
    {
        sprintf(filename,”enduse_%d.csv”,my->id);
        return SUCCESS;
    };
    intrinsic init(object parent)
    {
        OBJECT *weather = (OBJECT*)gl_get_addr(my->parent,”weather”);
        PANEL *panel = (PANEL*)((char*)weather+sizeof(OBJECT*));
        CIRCUIT *circuit;
        if ( parent==NULL || strcmp(parent->oclass->name,”house”)!=0 )
        {
            gl_error(”parent is not a house”);
            return FAILED;
        }
        fp = fopen(filename,”w”);
        if ( fp==NULL )
        {
            gl_error(”unable to open enduse monitoring output file ’%s’”, filename);
            return FAILED;
        }
        fprintf(fp,”# file...... %s\n# date...... \n# user...... \n# host...... \n# target.... \n”
                ”# trigger... \n# interval.. 3600\n# limit..... \n# timestamp”,filename);
        for ( circuit=panel->circuits ; circuit!=NULL ; circuit = circuit->next )
        {
            enduse *load = circuit->pLoad;
            fprintf(fp,”,%s”,load->name);
            load->energy = 0;
        }
        fprintf(fp,”%s”,”\n”);
        return SUCCESS;
    };
    intrinsic commit(TIMESTAMP t0, TIMESTAMP t1)
    {
        if ( t1%3600==0 )
        {
            // panel is not published but it follows weather, which is published
            OBJECT *weather = (OBJECT*)gl_get_addr(my->parent,”weather”);
            char buffer[256]=”INVALID”;
            PANEL *panel = (PANEL*)((char*)weather+sizeof(OBJECT*));
            CIRCUIT *circuit;
            struct tm *ts=localtime(&t1);
            fprintf(fp,”%04d-%02d-%02d %02d:%02d:%02d PST”,
                ts->tm_year+1900,ts->tm_mon+1,ts->tm_mday,
                ts->tm_hour,ts->tm_min,ts->tm_sec
                );
            for ( circuit=panel->circuits ; circuit!=NULL ; circuit = circuit->next )
            {
                enduse *load = circuit->pLoad;
                double diff = load->energy.Re() - energy[circuit->id];
                fprintf(fp,”,%g”,diff);
                energy[circuit->id] = load->energy.Re();
            }
            fprintf(fp,”%s”,”\n”);
        }
        return 3600*((t1/3600)+1);
    };
    intrinsic finalize()
    {
        fclose(fp);
        return SUCCESS;
    };
    private FILE *fp;
    private double energy[32];
}
```

B.2 Study Models

B.2.1 Seattle Winter

```
// generated by Matlab class Gridlabd on 30-Oct-2014 09:06:36
#set tmp=.
#include <C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\enduse_monitor.h>
#include "C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\enduse_monitor.glm"
#include "C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\schedules.glm"
#include "C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\house.glm"
#include "C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\market.glm"
clock {
        timezone PST+8PDT;
        starttime '2014-01-01 00:00:00';
        stoptime '2014-01-29 00:00:00';
}
module climate;
module powerflow {
        market_price_name "price";
}
module tape;
object climate {
        name "weather";
        tmyfile "WA-Seattle.tmy2";
        interpolate "QUADRATIC";
}
object triplex_meter {
        name "fixed_meter";
        phases "SA";
        bill_mode "UNIFORM";
        bill_day 1;
        price "81.0000 $/MWh";
        occupancy occupancy;
        nominal_voltage 120;
}
object house {
        name "fixed_house";
        parent "fixed_meter";
        floor_area 2400;
        thermal_integrity_level "GOOD";
        number_of_stories 2;
        heating_setpoint heating_setpoint;
        cooling_setpoint cooling_setpoint;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        occupancy occupancy;
        thermostat_deadband 1;
}
object recorder {
        parent "fixed_house";
        property "outdoor_temperature,air_temperature,heating_setpoint,cooling_setpoint,adj_heating_cap,adj_cooling
        interval 60;
        file "fixed_house.csv";
}
object recorder {
        parent "fixed_meter";
        property "measured_real_energy,price,monthly_bill,occupancy";
        interval 3600;
        file "fixed_meter.csv";
}
object enduse_monitor {
        parent "fixed_house";
        filename "fixed_enduse.csv";
}
object recorder {
        parent "fixed_house";
        property "envelope_UA,floor_area,UA,air_heat_capacity,mass_heat_coeff,mass_heat_capacity,design_heating_cap
        interval "-1";
        limit 1;
        file "design.csv";
}
object triplex_meter {
        name "tou_meter";
        phases "SA";
        bill_mode "UNIFORM";
        bill_day 1;
        price tou_tariff;
        occupancy occupancy;
        nominal_voltage 120;
}
object house {
        name "tou_house";
        parent "tou_meter";
        floor_area 2400;
        thermal_integrity_level "GOOD";
```

```
        number_of_stories 2;
        heating_setpoint heating_setpoint;
        cooling_setpoint cooling_setpoint;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        occupancy occupancy;
        thermostat_deadband 1;
}
object recorder {
        parent "tou_meter";
        property "measured_real_energy,price,monthly_bill";
        interval 3600;
        file "tou_meter.csv";
}
object triplex_meter {
        name "tou_meter_dr";
        phases "SA";
        bill_mode "UNIFORM";
        bill_day 1;
        price tou_tariff;
        occupancy occupancy;
        nominal_voltage 120;
}
object house {
        name "tou_house_dr";
        parent "tou_meter_dr";
        floor_area 2400;
        thermal_integrity_level "GOOD";
        number_of_stories 2;
        heating_setpoint heating_setback;
        cooling_setpoint cooling_setback;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        occupancy occupancy;
        thermostat_deadband 1;
}
object recorder {
        parent "tou_meter_dr";
        property "measured_real_energy,price,monthly_bill";
        interval 3600;
        file "tou_meter_dr.csv";
}
object recorder {
        parent "tou_house_dr";
        property "outdoor_temperature,air_temperature,heating_setpoint,cooling_setpoint,adj_heating_cap,adj_cooling_
        interval 60;
        file "tou_house.csv";
}
object market {
        name "retail";
        price "type:normal(0.080840,0.009984); refresh:5 min; min:0; max:999";
        price_mean 0.08084;
        price_stdev 0.00998374;
}
object triplex_meter {
        name "rtp_meter";
        phases "SA";
        bill_mode "HOURLY";
        bill_day 1;
        power_market "retail";
        occupancy occupancy;
        nominal_voltage 120;
}
object house {
        name "rtp_house";
        parent "rtp_meter";
        floor_area 2400;
        thermal_integrity_level "GOOD";
        number_of_stories 2;
        heating_setpoint heating_setpoint;
        cooling_setpoint cooling_setpoint;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        occupancy occupancy;
        thermostat_deadband 1;
}
object recorder {
        parent "rtp_meter";
        property "measured_real_energy,price,monthly_bill,occupancy";
        interval 300;
        file "rtp_meter.csv";
}
object triplex_meter {
        name "rtp_meter_dr";
        phases "SA";
        bill_mode "HOURLY";
```

```
        bill_day 1;
        power_market "retail";
        occupancy occupancy;
        nominal_voltage 120;
}
object house {
        name "rtp_house_dr";
        parent "rtp_meter_dr";
        floor_area 2400;
        thermal_integrity_level "GOOD";
        number_of_stories 2;
        heating_setpoint heating_setpoint;
        cooling_setpoint cooling_setpoint;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        thermostat_deadband 0.01;
        dlc_offset 0;
        k comfort;
        occupancy occupancy;
        override "OFF";
}
object rtp_thermostat {
        name "rtp_tstat";
        parent "rtp_house_dr";
        market "retail";
}
object recorder {
        parent "rtp_tstat";
        property "P,Pavg,Pstd,k,dlc_offset,Tout,Tair,Theat,Tcool,Taux,dTair,dTairMin,mode";
        interval 300;
        file "rtp_tstat.csv";
}
object recorder {
        parent "rtp_meter_dr";
        property "measured_real_energy,price,monthly_bill,occupancy";
        interval 300;
        file "rtp_meter_dr.csv";
}
object recorder {
        parent "rtp_house_dr";
        property "outdoor_temperature,air_temperature,heating_setpoint,cooling_setpoint,adj_heating_cap,adj_cooling
        interval 60;
        file "rtp_house.csv";
}
object triplex_meter {
        name "new_meter";
        phases "SA";
        bill_mode "HOURLY";
        bill_day 1;
        power_market "retail";
        occupancy occupancy;
        nominal_voltage 120;
}
object house {
        name "new_house";
        parent "new_meter";
        floor_area 2400;
        thermal_integrity_level "GOOD";
        number_of_stories 2;
        heating_setpoint heating_setpoint;
        cooling_setpoint cooling_setpoint;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        occupancy occupancy;
        thermostat_deadband 1;
}
object recorder {
        parent "new_meter";
        property "measured_real_energy,price,monthly_bill,occupancy";
        interval 300;
        file "new_meter.csv";
}
object triplex_meter {
        name "new_meter_dr";
        phases "SA";
        bill_mode "HOURLY";
        bill_day 1;
        power_market "retail";
        occupancy occupancy;
        nominal_voltage 120;
}
object house {
        name "new_house_dr";
        parent "new_meter_dr";
        floor_area 2400;
        thermal_integrity_level "GOOD";
        number_of_stories 2;
```

```
        heating_setpoint heating_setpoint;
        cooling_setpoint cooling_setpoint;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        thermostat_deadband 0.01;
        dlc_offset 0;
        k comfort;
        occupancy occupancy;
        override ”OFF”;
}
object new_thermostat {
        name ”new_tstat”;
        parent ”new_house_dr”;
        market ”retail”;
}
object recorder {
        parent ”new_tstat”;
        property ”P,Pavg,Pstd,k,dlc_offset,Tout,Tair,Theat,Tcool,Taux,dTair,dTairMin,mode”;
        interval 300;
        file ”new_tstat.csv”;
}
object recorder {
        parent ”new_meter_dr”;
        property ”measured_real_energy,price,monthly_bill,occupancy”;
        interval 300;
        file ”new_meter_dr.csv”;
}
object recorder {
        parent ”new_house_dr”;
        property ”outdoor_temperature,air_temperature,heating_setpoint,cooling_setpoint,adj_heating_cap,adj_cooling
        interval 60;
        file ”new_house.csv”;
}
```

B.2.2 Seattle Summer

```
// generated by Matlab class Gridlabd on 30-Oct-2014 09:06:52
#set tmp=.
#include <C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\enduse_monitor.h>
#include ”C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\enduse_monitor.glm”
#include ”C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\schedules.glm”
#include ”C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\house.glm”
#include ”C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\market.glm”
clock {
        timezone PST+8PDT;
        starttime ’2014-07-01 00:00:00’;
        stoptime ’2014-07-29 00:00:00’;
}
module climate;
module powerflow {
        market_price_name ”price”;
}
module tape;
object climate {
        name ”weather”;
        tmyfile ”WA-Seattle.tmy2”;
        interpolate ”QUADRATIC”;
}
object triplex_meter {
        name ”fixed_meter”;
        phases ”SA”;
        bill_mode ”UNIFORM”;
        bill_day 1;
        price ”81.0000 $/MWh”;
        occupancy occupancy;
        nominal_voltage 120;
}
object house {
        name ”fixed_house”;
        parent ”fixed_meter”;
        floor_area 2400;
        thermal_integrity_level ”GOOD”;
        number_of_stories 2;
        heating_setpoint heating_setpoint;
        cooling_setpoint cooling_setpoint;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        occupancy occupancy;
        thermostat_deadband 1;
}
object recorder {
        parent ”fixed_house”;
        property ”outdoor_temperature,air_temperature,heating_setpoint,cooling_setpoint,adj_heating_cap,adj_cooling
        interval 60;
        file ”fixed_house.csv”;
```

```
}
object recorder {
        parent "fixed_meter";
        property "measured_real_energy,price,monthly_bill,occupancy";
        interval 3600;
        file "fixed_meter.csv";
}
object enduse_monitor {
        parent "fixed_house";
        filename "fixed_enduse.csv";
}
object recorder {
        parent "fixed_house";
        property "envelope_UA,floor_area,UA,air_heat_capacity,mass_heat_coeff,mass_heat_capacity,design_heating_cap
        interval "-1";
        limit 1;
        file "design.csv";
}
object triplex_meter {
        name "tou_meter";
        phases "SA";
        bill_mode "UNIFORM";
        bill_day 1;
        price tou_tariff;
        occupancy occupancy;
        nominal_voltage 120;
}
object house {
        name "tou_house";
        parent "tou_meter";
        floor_area 2400;
        thermal_integrity_level "GOOD";
        number_of_stories 2;
        heating_setpoint heating_setpoint;
        cooling_setpoint cooling_setpoint;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        occupancy occupancy;
        thermostat_deadband 1;
}
object recorder {
        parent "tou_meter";
        property "measured_real_energy,price,monthly_bill";
        interval 3600;
        file "tou_meter.csv";
}
object triplex_meter {
        name "tou_meter_dr";
        phases "SA";
        bill_mode "UNIFORM";
        bill_day 1;
        price tou_tariff;
        occupancy occupancy;
        nominal_voltage 120;
}
object house {
        name "tou_house_dr";
        parent "tou_meter_dr";
        floor_area 2400;
        thermal_integrity_level "GOOD";
        number_of_stories 2;
        heating_setpoint heating_setback;
        cooling_setpoint cooling_setback;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        occupancy occupancy;
        thermostat_deadband 1;
}
object recorder {
        parent "tou_meter_dr";
        property "measured_real_energy,price,monthly_bill";
        interval 3600;
        file "tou_meter_dr.csv";
}
object recorder {
        parent "tou_house_dr";
        property "outdoor_temperature,air_temperature,heating_setpoint,cooling_setpoint,adj_heating_cap,adj_cooling_
        interval 60;
        file "tou_house.csv";
}
object market {
        name "retail";
        price "type:normal(0.080840,0.009984); refresh:5 min; min:0; max:999";
        price_mean 0.08084;
        price_stdev 0.00998374;
}
object triplex_meter {
```

```
	name "rtp_meter";
	phases "SA";
	bill_mode "HOURLY";
	bill_day 1;
	power_market "retail";
	occupancy occupancy;
	nominal_voltage 120;
}
object house {
	name "rtp_house";
	parent "rtp_meter";
	floor_area 2400;
	thermal_integrity_level "GOOD";
	number_of_stories 2;
	heating_setpoint heating_setpoint;
	cooling_setpoint cooling_setpoint;
	design_heating_capacity 0;
	design_cooling_capacity 0;
	air_temperature 75;
	occupancy occupancy;
	thermostat_deadband 1;
}
object recorder {
	parent "rtp_meter";
	property "measured_real_energy,price,monthly_bill,occupancy";
	interval 300;
	file "rtp_meter.csv";
}
object triplex_meter {
	name "rtp_meter_dr";
	phases "SA";
	bill_mode "HOURLY";
	bill_day 1;
	power_market "retail";
	occupancy occupancy;
	nominal_voltage 120;
}
object house {
	name "rtp_house_dr";
	parent "rtp_meter_dr";
	floor_area 2400;
	thermal_integrity_level "GOOD";
	number_of_stories 2;
	heating_setpoint heating_setpoint;
	cooling_setpoint cooling_setpoint;
	design_heating_capacity 0;
	design_cooling_capacity 0;
	air_temperature 75;
	thermostat_deadband 0.01;
	dlc_offset 0;
	k comfort;
	occupancy occupancy;
	override "OFF";
}
object rtp_thermostat {
	name "rtp_tstat";
	parent "rtp_house_dr";
	market "retail";
}
object recorder {
	parent "rtp_tstat";
	property "P,Pavg,Pstd,k,dlc_offset,Tout,Tair,Theat,Tcool,Taux,dTair,dTairMin,mode";
	interval 300;
	file "rtp_tstat.csv";
}
object recorder {
	parent "rtp_meter_dr";
	property "measured_real_energy,price,monthly_bill,occupancy";
	interval 300;
	file "rtp_meter_dr.csv";
}
object recorder {
	parent "rtp_house_dr";
	property "outdoor_temperature,air_temperature,heating_setpoint,cooling_setpoint,adj_heating_cap,adj_cooling_
	interval 60;
	file "rtp_house.csv";
}
object triplex_meter {
	name "new_meter";
	phases "SA";
	bill_mode "HOURLY";
	bill_day 1;
	power_market "retail";
	occupancy occupancy;
	nominal_voltage 120;
}
object house {
	name "new_house";
	parent "new_meter";
```

```
	floor_area 2400;
	thermal_integrity_level "GOOD";
	number_of_stories 2;
	heating_setpoint heating_setpoint;
	cooling_setpoint cooling_setpoint;
	design_heating_capacity 0;
	design_cooling_capacity 0;
	air_temperature 75;
	occupancy occupancy;
	thermostat_deadband 1;
}
object recorder {
	parent "new_meter";
	property "measured_real_energy,price,monthly_bill,occupancy";
	interval 300;
	file "new_meter.csv";
}
object triplex_meter {
	name "new_meter_dr";
	phases "SA";
	bill_mode "HOURLY";
	bill_day 1;
	power_market "retail";
	occupancy occupancy;
	nominal_voltage 120;
}
object house {
	name "new_house_dr";
	parent "new_meter_dr";
	floor_area 2400;
	thermal_integrity_level "GOOD";
	number_of_stories 2;
	heating_setpoint heating_setpoint;
	cooling_setpoint cooling_setpoint;
	design_heating_capacity 0;
	design_cooling_capacity 0;
	air_temperature 75;
	thermostat_deadband 0.01;
	dlc_offset 0;
	k comfort;
	occupancy occupancy;
	override "OFF";
}
object new_thermostat {
	name "new_tstat";
	parent "new_house_dr";
	market "retail";
}
object recorder {
	parent "new_tstat";
	property "P,Pavg,Pstd,k,dlc_offset,Tout,Tair,Theat,Tcool,Taux,dTair,dTairMin,mode";
	interval 300;
	file "new_tstat.csv";
}
object recorder {
	parent "new_meter_dr";
	property "measured_real_energy,price,monthly_bill,occupancy";
	interval 300;
	file "new_meter_dr.csv";
}
object recorder {
	parent "new_house_dr";
	property "outdoor_temperature,air_temperature,heating_setpoint,cooling_setpoint,adj_heating_cap,adj_cooling
	interval 60;
	file "new_house.csv";
}
```

B.2.3 Phoenix Summer

```
// generated by Matlab class Gridlabd on 30-Oct-2014 09:07:22
#set tmp=.
#include <C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\enduse_monitor.h>
#include "C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\enduse_monitor.glm"
#include "C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\schedules.glm"
#include "C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\house.glm"
#include "C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\market.glm"
clock {
	timezone MST+7;
	starttime '2014-07-01 00:00:00';
	stoptime '2014-07-29 00:00:00';
}
module climate;
module powerflow {
	market_price_name "price";
}
module tape;
object climate {
```

```
        name "weather";
        tmyfile "AZ-Phoenix.tmy2";
        interpolate "QUADRATIC";
}
object triplex_meter {
        name "fixed_meter";
        phases "SA";
        bill_mode "UNIFORM";
        bill_day 1;
        price "82.3800 $/MWh";
        occupancy occupancy;
        nominal_voltage 120;
}
object house {
        name "fixed_house";
        parent "fixed_meter";
        floor_area 2400;
        thermal_integrity_level "VERY_GOOD";
        number_of_stories 2;
        heating_setpoint heating_setpoint;
        cooling_setpoint cooling_setpoint;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        occupancy occupancy;
        thermostat_deadband 1;
}
object recorder {
        parent "fixed_house";
        property "outdoor_temperature,air_temperature,heating_setpoint,cooling_setpoint,adj_heating_cap,adj_cooling
        interval 60;
        file "fixed_house.csv";
}
object recorder {
        parent "fixed_meter";
        property "measured_real_energy,price,monthly_bill,occupancy";
        interval 3600;
        file "fixed_meter.csv";
}
object enduse_monitor {
        parent "fixed_house";
        filename "fixed_enduse.csv";
}
object recorder {
        parent "fixed_house";
        property "envelope_UA,floor_area,UA,air_heat_capacity,mass_heat_coeff,mass_heat_capacity,design_heating_cap
        interval "-1";
        limit 1;
        file "design.csv";
}
object triplex_meter {
        name "tou_meter";
        phases "SA";
        bill_mode "UNIFORM";
        bill_day 1;
        price tou_tariff;
        occupancy occupancy;
        nominal_voltage 120;
}
object house {
        name "tou_house";
        parent "tou_meter";
        floor_area 2400;
        thermal_integrity_level "VERY_GOOD";
        number_of_stories 2;
        heating_setpoint heating_setpoint;
        cooling_setpoint cooling_setpoint;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        occupancy occupancy;
        thermostat_deadband 1;
}
object recorder {
        parent "tou_meter";
        property "measured_real_energy,price,monthly_bill";
        interval 3600;
        file "tou_meter.csv";
}
object triplex_meter {
        name "tou_meter_dr";
        phases "SA";
        bill_mode "UNIFORM";
        bill_day 1;
        price tou_tariff;
        occupancy occupancy;
        nominal_voltage 120;
}
object house {
```

```
        name ”tou_house_dr”;
        parent ”tou_meter_dr”;
        floor_area 2400;
        thermal_integrity_level ”VERY_GOOD”;
        number_of_stories 2;
        heating_setpoint heating_setback;
        cooling_setpoint cooling_setback;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        occupancy occupancy;
        thermostat_deadband 1;
}
object recorder {
        parent ”tou_meter_dr”;
        property ”measured_real_energy,price,monthly_bill”;
        interval 3600;
        file ”tou_meter_dr.csv”;
}
object recorder {
        parent ”tou_house_dr”;
        property ”outdoor_temperature,air_temperature,heating_setpoint,cooling_setpoint,adj_heating_cap,adj_cooling_
        interval 60;
        file ”tou_house.csv”;
}
object market {
        name ”retail”;
        price ”type:normal(0.082220,0.010154); refresh:5 min; min:0; max:999”;
        price_mean 0.08222;
        price_stdev 0.0101542;
}
object triplex_meter {
        name ”rtp_meter”;
        phases ”SA”;
        bill_mode ”HOURLY”;
        bill_day 1;
        power_market ”retail”;
        occupancy occupancy;
        nominal_voltage 120;
}
object house {
        name ”rtp_house”;
        parent ”rtp_meter”;
        floor_area 2400;
        thermal_integrity_level ”VERY_GOOD”;
        number_of_stories 2;
        heating_setpoint heating_setpoint;
        cooling_setpoint cooling_setpoint;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        occupancy occupancy;
        thermostat_deadband 1;
}
object recorder {
        parent ”rtp_meter”;
        property ”measured_real_energy,price,monthly_bill,occupancy”;
        interval 300;
        file ”rtp_meter.csv”;
}
object triplex_meter {
        name ”rtp_meter_dr”;
        phases ”SA”;
        bill_mode ”HOURLY”;
        bill_day 1;
        power_market ”retail”;
        occupancy occupancy;
        nominal_voltage 120;
}
object house {
        name ”rtp_house_dr”;
        parent ”rtp_meter_dr”;
        floor_area 2400;
        thermal_integrity_level ”VERY_GOOD”;
        number_of_stories 2;
        heating_setpoint heating_setpoint;
        cooling_setpoint cooling_setpoint;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        thermostat_deadband 0.01;
        dlc_offset 0;
        k comfort;
        occupancy occupancy;
        override ”OFF”;
}
object rtp_thermostat {
        name ”rtp_tstat”;
        parent ”rtp_house_dr”;
```

```
        market "retail";
}
object recorder {
        parent "rtp_tstat";
        property "P,Pavg,Pstd,k,dlc_offset,Tout,Tair,Theat,Tcool,Taux,dTair,dTairMin,mode";
        interval 300;
        file "rtp_tstat.csv";
}
object recorder {
        parent "rtp_meter_dr";
        property "measured_real_energy,price,monthly_bill,occupancy";
        interval 300;
        file "rtp_meter_dr.csv";
}
object recorder {
        parent "rtp_house_dr";
        property "outdoor_temperature,air_temperature,heating_setpoint,cooling_setpoint,adj_heating_cap,adj_cooling_
        interval 60;
        file "rtp_house.csv";
}
object triplex_meter {
        name "new_meter";
        phases "SA";
        bill_mode "HOURLY";
        bill_day 1;
        power_market "retail";
        occupancy occupancy;
        nominal_voltage 120;
}
object house {
        name "new_house";
        parent "new_meter";
        floor_area 2400;
        thermal_integrity_level "VERY_GOOD";
        number_of_stories 2;
        heating_setpoint heating_setpoint;
        cooling_setpoint cooling_setpoint;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        occupancy occupancy;
        thermostat_deadband 1;
}
object recorder {
        parent "new_meter";
        property "measured_real_energy,price,monthly_bill,occupancy";
        interval 300;
        file "new_meter.csv";
}
object triplex_meter {
        name "new_meter_dr";
        phases "SA";
        bill_mode "HOURLY";
        bill_day 1;
        power_market "retail";
        occupancy occupancy;
        nominal_voltage 120;
}
object house {
        name "new_house_dr";
        parent "new_meter_dr";
        floor_area 2400;
        thermal_integrity_level "VERY_GOOD";
        number_of_stories 2;
        heating_setpoint heating_setpoint;
        cooling_setpoint cooling_setpoint;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        thermostat_deadband 0.01;
        dlc_offset 0;
        k comfort;
        occupancy occupancy;
        override "OFF";
}
object new_thermostat {
        name "new_tstat";
        parent "new_house_dr";
        market "retail";
}
object recorder {
        parent "new_tstat";
        property "P,Pavg,Pstd,k,dlc_offset,Tout,Tair,Theat,Tcool,Taux,dTair,dTairMin,mode";
        interval 300;
        file "new_tstat.csv";
}
object recorder {
        parent "new_meter_dr";
        property "measured_real_energy,price,monthly_bill,occupancy";
```

```
        interval 300;
        file "new_meter_dr.csv";
}
object recorder {
        parent "new_house_dr";
        property "outdoor_temperature,air_temperature,heating_setpoint,cooling_setpoint,adj_heating_cap,adj_cooling_
        interval 60;
        file "new_house.csv";
}
```

B.2.4 Miami Summer

```
// generated by Matlab class Gridlabd on 30-Oct-2014 09:07:06
#set tmp=.
#include <C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\enduse_monitor.h>
#include "C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\enduse_monitor.glm"
#include "C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\schedules.glm"
#include "C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\house.glm"
#include "C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\market.glm"
clock {
        timezone EST+5EDT;
        starttime '2014-07-01 00:00:00';
        stoptime '2014-07-29 00:00:00';
}
module climate;
module powerflow {
        market_price_name "price";
}
module tape;
object climate {
        name "weather";
        tmyfile "FL-Miami.tmy2";
        interpolate "QUADRATIC";
}
object triplex_meter {
        name "fixed_meter";
        phases "SA";
        bill_mode "UNIFORM";
        bill_day 1;
        price "78.8100 $/MWh";
        occupancy occupancy;
        nominal_voltage 120;
}
object house {
        name "fixed_house";
        parent "fixed_meter";
        floor_area 2400;
        thermal_integrity_level "VERY_GOOD";
        number_of_stories 2;
        heating_setpoint heating_setpoint;
        cooling_setpoint cooling_setpoint;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        occupancy occupancy;
        thermostat_deadband 1;
}
object recorder {
        parent "fixed_house";
        property "outdoor_temperature,air_temperature,heating_setpoint,cooling_setpoint,adj_heating_cap,adj_cooling_
        interval 60;
        file "fixed_house.csv";
}
object recorder {
        parent "fixed_meter";
        property "measured_real_energy,price,monthly_bill,occupancy";
        interval 3600;
        file "fixed_meter.csv";
}
object enduse_monitor {
        parent "fixed_house";
        filename "fixed_enduse.csv";
}
object recorder {
        parent "fixed_house";
        property "envelope_UA,floor_area,UA,air_heat_capacity,mass_heat_coeff,mass_heat_capacity,design_heating_cap
        interval "-1";
        limit 1;
        file "design.csv";
}
object triplex_meter {
        name "tou_meter";
        phases "SA";
        bill_mode "UNIFORM";
        bill_day 1;
        price tou_tariff;
        occupancy occupancy;
```

```
        nominal_voltage 120;
}
object house {
        name "tou_house";
        parent "tou_meter";
        floor_area 2400;
        thermal_integrity_level "VERY_GOOD";
        number_of_stories 2;
        heating_setpoint heating_setpoint;
        cooling_setpoint cooling_setpoint;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        occupancy occupancy;
        thermostat_deadband 1;
}
object recorder {
        parent "tou_meter";
        property "measured_real_energy,price,monthly_bill";
        interval 3600;
        file "tou_meter.csv";
}
object triplex_meter {
        name "tou_meter_dr";
        phases "SA";
        bill_mode "UNIFORM";
        bill_day 1;
        price tou_tariff;
        occupancy occupancy;
        nominal_voltage 120;
}
object house {
        name "tou_house_dr";
        parent "tou_meter_dr";
        floor_area 2400;
        thermal_integrity_level "VERY_GOOD";
        number_of_stories 2;
        heating_setpoint heating_setback;
        cooling_setpoint cooling_setback;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        occupancy occupancy;
        thermostat_deadband 1;
}
object recorder {
        parent "tou_meter_dr";
        property "measured_real_energy,price,monthly_bill";
        interval 3600;
        file "tou_meter_dr.csv";
}
object recorder {
        parent "tou_house_dr";
        property "outdoor_temperature,air_temperature,heating_setpoint,cooling_setpoint,adj_heating_cap,adj_cooling_
        interval 60;
        file "tou_house.csv";
}
object market {
        name "retail";
        price "type:normal(0.078730,0.009723); refresh:5 min; min:0; max:999";
        price_mean 0.07873;
        price_stdev 0.00972316;
}
object triplex_meter {
        name "rtp_meter";
        phases "SA";
        bill_mode "HOURLY";
        bill_day 1;
        power_market "retail";
        occupancy occupancy;
        nominal_voltage 120;
}
object house {
        name "rtp_house";
        parent "rtp_meter";
        floor_area 2400;
        thermal_integrity_level "VERY_GOOD";
        number_of_stories 2;
        heating_setpoint heating_setpoint;
        cooling_setpoint cooling_setpoint;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        occupancy occupancy;
        thermostat_deadband 1;
}
object recorder {
        parent "rtp_meter";
        property "measured_real_energy,price,monthly_bill,occupancy";
```

```
        interval 300;
        file "rtp_meter.csv";
}
object triplex_meter {
        name "rtp_meter_dr";
        phases "SA";
        bill_mode "HOURLY";
        bill_day 1;
        power_market "retail";
        occupancy occupancy;
        nominal_voltage 120;
}
object house {
        name "rtp_house_dr";
        parent "rtp_meter_dr";
        floor_area 2400;
        thermal_integrity_level "VERY_GOOD";
        number_of_stories 2;
        heating_setpoint heating_setpoint;
        cooling_setpoint cooling_setpoint;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        thermostat_deadband 0.01;
        dlc_offset 0;
        k comfort;
        occupancy occupancy;
        override "OFF";
}
object rtp_thermostat {
        name "rtp_tstat";
        parent "rtp_house_dr";
        market "retail";
}
object recorder {
        parent "rtp_tstat";
        property "P,Pavg,Pstd,k,dlc_offset,Tout,Tair,Theat,Tcool,Taux,dTair,dTairMin,mode";
        interval 300;
        file "rtp_tstat.csv";
}
object recorder {
        parent "rtp_meter_dr";
        property "measured_real_energy,price,monthly_bill,occupancy";
        interval 300;
        file "rtp_meter_dr.csv";
}
object recorder {
        parent "rtp_house_dr";
        property "outdoor_temperature,air_temperature,heating_setpoint,cooling_setpoint,adj_heating_cap,adj_cooling
        interval 60;
        file "rtp_house.csv";
}
object triplex_meter {
        name "new_meter";
        phases "SA";
        bill_mode "HOURLY";
        bill_day 1;
        power_market "retail";
        occupancy occupancy;
        nominal_voltage 120;
}
object house {
        name "new_house";
        parent "new_meter";
        floor_area 2400;
        thermal_integrity_level "VERY_GOOD";
        number_of_stories 2;
        heating_setpoint heating_setpoint;
        cooling_setpoint cooling_setpoint;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        occupancy occupancy;
        thermostat_deadband 1;
}
object recorder {
        parent "new_meter";
        property "measured_real_energy,price,monthly_bill,occupancy";
        interval 300;
        file "new_meter.csv";
}
object triplex_meter {
        name "new_meter_dr";
        phases "SA";
        bill_mode "HOURLY";
        bill_day 1;
        power_market "retail";
        occupancy occupancy;
        nominal_voltage 120;
```

```
}
object house {
        name "new_house_dr";
        parent "new_meter_dr";
        floor_area 2400;
        thermal_integrity_level "VERY_GOOD";
        number_of_stories 2;
        heating_setpoint heating_setpoint;
        cooling_setpoint cooling_setpoint;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature 75;
        thermostat_deadband 0.01;
        dlc_offset 0;
        k comfort;
        occupancy occupancy;
        override "OFF";
}
object new_thermostat {
        name "new_tstat";
        parent "new_house_dr";
        market "retail";
}
object recorder {
        parent "new_tstat";
        property "P,Pavg,Pstd,k,dlc_offset,Tout,Tair,Theat,Tcool,Taux,dTair,dTairMin,mode";
        interval 300;
        file "new_tstat.csv";
}
object recorder {
        parent "new_meter_dr";
        property "measured_real_energy,price,monthly_bill,occupancy";
        interval 300;
        file "new_meter_dr.csv";
}
object recorder {
        parent "new_house_dr";
        property "outdoor_temperature,air_temperature,heating_setpoint,cooling_setpoint,adj_heating_cap,adj_cooling_
        interval 60;
        file "new_house.csv";
}
```

B.2.5 Feeder Response

```
// FEEDER TEST
#define NHOMES=100
#set tmp=.
#include <C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\enduse_monitor.h>
#include "C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\enduse_monitor.glm"
#include "C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\schedules.glm"
#include "C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\house.glm"
#include "C:\Users\dchassin\Desktop\Dropbox\UVic\Courses\MECH599\Thesis\evaluation\matlab\market.glm"
clock {
        timezone MST+7;
        starttime '2014-07-01 00:00:00';
        stoptime '2014-07-02 00:00:00';
}
module climate;
module powerflow {
        market_price_name "price";
}
module tape;
object climate {
        name "weather";
        tmyfile "AZ-Phoenix.tmy2";
        interpolate "QUADRATIC";
}

// MARKET
object market {
        name "retail";
        price "type:normal(0.078730,0.009723); refresh:5 min; min:0; max:999";
        price_mean 0.07873;
        price_stdev 0.00972316;
    object recorder {
        property price;
        interval 4;
        file "price.csv";
    };
}

// RTP HOUSES
object triplex_meter:..${NHOMES} {
    groupid 1;
        phases "SA";
        bill_mode "HOURLY";
```

```
        bill_day 1;
        power_market "retail";
        occupancy occupancy;
        nominal_voltage 120;
    object house {
        floor_area random.uniform(1200,3600);
        thermal_integrity_level "VERY_GOOD";
        number_of_stories 2;
        heating_setpoint heating_setpoint;
        cooling_setpoint cooling_setpoint;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature random.uniform(72,78);
        thermostat_deadband 1;
        dlc_offset 0;
        k comfort;
        occupancy occupancy;
        override "OFF";
        object rtp_thermostat {
            market "retail";
        };
    };
}

// NEW HOUSES
object triplex_meter:..${NHOMES} {
    groupid 2;
        phases "SA";
        bill_mode "HOURLY";
        bill_day 1;
        power_market "retail";
        occupancy occupancy;
        nominal_voltage 120;
    object house {
        floor_area random.uniform(1200,3600);
        thermal_integrity_level "VERY_GOOD";
        number_of_stories 2;
        heating_setpoint heating_setpoint;
        cooling_setpoint cooling_setpoint;
        design_heating_capacity 0;
        design_cooling_capacity 0;
        air_temperature random.uniform(72,78);
        thermostat_deadband 0.01;
        dlc_offset 0;
        k comfort;
        occupancy occupancy;
        override "OFF";
        object new_thermostat {
            market "retail";
        };
    };
}

// DATA COLLECTORS
object collector {
    group "class=triplex_meter and groupid=1";
    property "sum(measured_real_power)";
    interval 4;
    file "feeder_rtp.csv";
}
object collector {
    group "class=triplex_meter and groupid=2";
    property "sum(measured_real_power)";
    interval 4;
    file "feeder_new.csv";
}
```

B.3 Modifications to GridLAB-D

```
Index: core/load.c
===================================================================
--- core/load.c (revision 4854)
+++ core/load.c (working copy)
@@ -898,6 +898,11 @@
        }
        else
                oclass->has_runtime = false;
+
+       /* clear buffers */
+       code_block[0] = global_block[0] = init_block[0] = '\0';
+       code_used = 0;
+
        return SUCCESS;
 }

```

```
Index: core/rt/gridlabd.h
===================================================================
--- core/rt/gridlabd.h  (revision 4854)
+++ core/rt/gridlabd.h  (working copy)
@@ -824,22 +824,81 @@
        loadshape *next;        /* next loadshape in list */
 };

-struct s_enduse {
-       loadshape *shape;
-       complex power;                          /* power in kW */
-       complex energy;                         /* total energy in kWh */
-       complex demand;                         /* maximum power in kW (can be reset) */
-       double impedance_fraction;      /* constant impedance fraction (pu load) */
-       double current_fraction;        /* constant current fraction (pu load) */
-       double power_fraction;          /* constant power fraction (pu load)*/
-       double power_factor;            /* power factor */
-       double voltage_factor;          /* voltage factor (pu nominal) */
-       double heatgain;                        /* internal heat from load (Btu/h) */
-       double heatgain_fraction;       /* fraction of power that goes to internal heat (pu Btu/h) */
+typedef enum {
+       EUMT_MOTOR_A, /**< 3ph induction motors driving constant torque loads */
+       EUMT_MOTOR_B, /**< induction motors driving high inertia speed-squares torque loads */
+       EUMT_MOTOR_C, /**< induction motors driving low inertia loads speed-squared torque loads */
+       EUMT_MOTOR_D, /**< 1ph induction motors driving constant torque loads */
+       _EUMT_COUNT, /* must be last */
+} EUMOTORTYPE;
+typedef enum {
+    EUET_ELECTRONIC_A, /**< simple power electronics (no backfeed) */
+    EUET_ELECTRONIC_B, /**< advanced power electronics (w/ backfeed) */
+    _EUET_COUNT, /* must be last */
+} EUELECTRONICTYPE;
+typedef struct s_motor {
+    complex power;             /**< motor power when running */
+    complex impedance; /**< motor impedance when stalled */
+    double inertia;            /**< motor inertia in seconds */
+    double v_stall;            /**< motor stall voltage (pu) */
+    double v_start;            /**< motor start voltage (pu) */
+    double v_trip;             /**< motor trip voltage (pu) */
+    double t_trip;             /**< motor thermal trip time in seconds */
+    /* TODO add slip data (0 for synchronous motors) */
+} EUMOTOR;
+typedef struct s_electronic {
+    complex power;             /**< load power when running */
+    double inertia;            /**< load "inertia" */
+    double v_trip;             /**< load "trip" voltage (pu) */
+    double v_start;            /**< load "start" voltage (pu) */
+} EUELECTRONIC;

-       enduse *next;
-};
-
+typedef struct s_enduse {
+       /* the output value must be first for transform to stream */
+       /* meter values */
+       complex total;                          /* total power in kW */
+       complex energy;                         /* total energy in kWh */
+       complex demand;                         /* maximum power in kW (can be reset) */
+
+       /* circuit configuration */
+       set config;                                     /* end-use configuration */
+       double breaker_amps;            /* breaker limit (if any) */
+
+       /* zip values */
+       complex admittance;                     /* constant impedance oprtion of load in kW */
+       complex current;                        /* constant current portion of load in kW */
+       complex power;                          /* constant power portion of load in kW */
+
+       /* composite load data */
+       EUMOTOR motor[_EUMT_COUNT];                             /* motor loads (A-D) */
+       EUELECTRONIC electronic[_EUET_COUNT];   /* electronic loads (S/D) */
+
+       /* loading */
+       double impedance_fraction;      /* constant impedance fraction (pu load) */
+       double current_fraction;        /* constant current fraction (pu load) */
+       double power_fraction;          /* constant power fraction (pu load)*/
+       double power_factor;            /* power factor */
+       double voltage_factor;          /* voltage factor (pu nominal) */
+
+       /* heat */
+       double heatgain;                        /* internal heat from load (Btu/h) */
+       double cumulative_heatgain;  /* internal cumulative heat gain from load (Btu) */
+       double heatgain_fraction;       /* fraction of power that goes to internal heat (pu Btu/h) */
+
+       /* misc info */
+       char *name;
+       loadshape *shape;
+       TIMESTAMP t_last;                       /* last time of update */
+
```

```
+       // added for backward compatibility with res ENDUSELOAD
+       // @todo these are obsolete and must be retrofitted with the above values
+       struct s_object_list *end_obj;
+
+       struct s_enduse *next;
+#ifdef _DEBUG
+       unsigned int magic;
+#endif
+} enduse;
 /* object flags */
 #define OF_NONE                0x0000 /**< Object flag; none set */
 #define OF_HASPLC      0x0001 /**< Object flag; external PLC is attached, disables local PLC */
Index: powerflow/triplex_meter.cpp
===================================================================
--- powerflow/triplex_meter.cpp (revision 4854)
+++ powerflow/triplex_meter.cpp (working copy)
@@ -36,6 +36,8 @@
        return 0;
 }

+static char1024 market_price_name = "current_market.clearing_price";
+
 //////////////////////////////////////////////////////////////////////////
 // triplex_meter CLASS FUNCTIONS
 //////////////////////////////////////////////////////////////////////////
@@ -122,6 +124,9 @@
                                GL_THROW("Unable to publish triplex_meter deltamode function");
                        if (gl_publish_function(oclass, "delta_freq_pwr_object", (FUNCTIONADDR)delta_frequency_node
                                GL_THROW("Unable to publish triplex_meter deltamode function");
+
+                       // market price name
+                       gl_global_create("powerflow::market_price_name",PT_char1024,&market_price_name,NULL);
                }
 }

@@ -179,9 +184,9 @@
 #endif

        if(power_market != 0){
-               price_prop = gl_get_property(power_market, "current_market.clearing_price");
+               price_prop = gl_get_property(power_market, market_price_name);
                if(price_prop == 0){
-                       GL_THROW("triplex_meter::power_market object \'%s\' does not publish \'current_market.clear
+                       GL_THROW("triplex_meter::power_market object \'%s\' does not publish \'%s\'", (power_market
                }
        }
        check_prices();
Index: residential/bsra2014.h
===================================================================
--- residential/bsra2014.h      (revision 0)
+++ residential/bsra2014.h      (working copy)
@@ -0,0 +1,401 @@
+// $Id$
+//
+// This file contains the BSRA 2014 enduse daily energy uses over ELCAP load shapes (see NEEA 2014)
+//
+//                                     NEEA 2014
+//                     Daily energy    Fraction
+// Enduse              (kWh/d)         of ELCAP        Remarks
+// --------------      ------------    --------        -----------------------
+// Refrigerator                1.7             0.43
+// Freezer                     1.4             0.38
+// Dishwasher          0.65            1.80
+// Clotheswasher    0.15                       0.50
+// Dryer                       2.0                             0.64
+// Oven                                0.8                             0.56            Does not include microwaves
+// Waterheater         8.0                             0.56
+// Plugs            2.5                        Does not include lights
+//   TV                                0.6
+//   Cable/DVR         0.7
+//   Game                      0.2
+//   Computer          0.9
+//   DVD                       0.1
+//
+// lighting (source: ELCAP lit-sp.dat)
+{      "LIGHTS",
+       {30, false, {0.5,0.1,0.4}, 0.97, 0.9},
+       "type:analog; schedule: residential-lights-default; power: 0.25 kW", // 1/8 power, 2x lights
+       "residential-lights-default",
+       "positive; nonzero; weekday-summer {"
+       "*  0 * 4-9 1-5 0.380; *  1 * 4-9 1-5 0.340; *  2 * 4-9 1-5 0.320; *  3 * 4-9 1-5 0.320;"
+       "*  4 * 4-9 1-5 0.320; *  5 * 4-9 1-5 0.350; *  6 * 4-9 1-5 0.410; *  7 * 4-9 1-5 0.450;"
+       "*  8 * 4-9 1-5 0.450; *  9 * 4-9 1-5 0.450; * 10 * 4-9 1-5 0.450; * 11 * 4-9 1-5 0.450;"
+       "* 12 * 4-9 1-5 0.450; * 13 * 4-9 1-5 0.440; * 14 * 4-9 1-5 0.440; * 15 * 4-9 1-5 0.450;"
+       "* 16 * 4-9 1-5 0.470; * 17 * 4-9 1-5 0.510; * 18 * 4-9 1-5 0.540; * 19 * 4-9 1-5 0.560;"
+       "* 20 * 4-9 1-5 0.630; * 21 * 4-9 1-5 0.710; * 22 * 4-9 1-5 0.650; * 23 * 4-9 1-5 0.490"
+       "}"
+       "weekend-summer {"
+       "*  0 * 4-9 6-0 0.410; *  1 * 4-9 6-0 0.360; *  2 * 4-9 6-0 0.330; *  3 * 4-9 6-0 0.320;"
```

```
+        "*  4 * 4-9 6-0 0.320; *  5 * 4-9 6-0 0.320; *  6 * 4-9 6-0 0.340; *  7 * 4-9 6-0 0.390;"
+        "*  8 * 4-9 6-0 0.440; *  9 * 4-9 6-0 0.470; * 10 * 4-9 6-0 0.470; * 11 * 4-9 6-0 0.470;"
+        "* 12 * 4-9 6-0 0.470; * 13 * 4-9 6-0 0.460; * 14 * 4-9 6-0 0.460; * 15 * 4-9 6-0 0.460;"
+        "* 16 * 4-9 6-0 0.470; * 17 * 4-9 6-0 0.490; * 18 * 4-9 6-0 0.520; * 19 * 4-9 6-0 0.540;"
+        "* 20 * 4-9 6-0 0.610; * 21 * 4-9 6-0 0.680; * 22 * 4-9 6-0 0.630; * 23 * 4-9 6-0 0.500"
+        "}"
+        "weekday-winter {"
+        "*  0 * 10-3 1-5 0.4200; *  1 * 10-3 1-5 0.3800; *  2 * 10-3 1-5 0.3700; *  3 * 10-3 1-5 0.3600;"
+        "*  4 * 10-3 1-5 0.3700; *  5 * 10-3 1-5 0.4200; *  6 * 10-3 1-5 0.5800; *  7 * 10-3 1-5 0.6900;"
+        "*  8 * 10-3 1-5 0.6100; *  9 * 10-3 1-5 0.5600; * 10 * 10-3 1-5 0.5300; * 11 * 10-3 1-5 0.5100;"
+        "* 12 * 10-3 1-5 0.4900; * 13 * 10-3 1-5 0.4700; * 14 * 10-3 1-5 0.4700; * 15 * 10-3 1-5 0.5100;"
+        "* 16 * 10-3 1-5 0.6300; * 17 * 10-3 1-5 0.8400; * 18 * 10-3 1-5 0.9700; * 19 * 10-3 1-5 0.9800;"
+        "* 20 * 10-3 1-5 0.9600; * 21 * 10-3 1-5 0.8900; * 22 * 10-3 1-5 0.7400; * 23 * 10-3 1-5 0.5500"
+        "}"
+        "weekend-winter {"
+        "*  0 * 10-3 6-0 0.4900; *  1 * 10-3 6-0 0.4200; *  2 * 10-3 6-0 0.3800; *  3 * 10-3 6-0 0.3800;"
+        "*  4 * 10-3 6-0 0.3700; *  5 * 10-3 6-0 0.3800; *  6 * 10-3 6-0 0.4300; *  7 * 10-3 6-0 0.5100;"
+        "*  8 * 10-3 6-0 0.6000; *  9 * 10-3 6-0 0.6300; * 10 * 10-3 6-0 0.6300; * 11 * 10-3 6-0 0.6100;"
+        "* 12 * 10-3 6-0 0.6000; * 13 * 10-3 6-0 0.5900; * 14 * 10-3 6-0 0.5900; * 15 * 10-3 6-0 0.6100;"
+        "* 16 * 10-3 6-0 0.7100; * 17 * 10-3 6-0 0.8800; * 18 * 10-3 6-0 0.9600; * 19 * 10-3 6-0 0.9700;"
+        "* 20 * 10-3 6-0 0.9400; * 21 * 10-3 6-0 0.8800; * 22 * 10-3 6-0 0.7600; * 23 * 10-3 6-0 0.5800"
+        "}"
+        },
+        // Plugs (source: ELCAP lit-sp.dat)
+{       "PLUGS",
+        {30, false, {0.0,0.0,1.0}, 0.90, 0.9},
+        "type:analog; schedule: residential-plugs-default; power: 1.5 kW", // 50% more load
+        "residential-plugs-default",
+        "positive; nonzero; weekday-summer {"
+        "*  0 * 4-9 1-5 0.380; *  1 * 4-9 1-5 0.340; *  2 * 4-9 1-5 0.320; *  3 * 4-9 1-5 0.320;"
+        "*  4 * 4-9 1-5 0.320; *  5 * 4-9 1-5 0.350; *  6 * 4-9 1-5 0.410; *  7 * 4-9 1-5 0.450;"
+        "*  8 * 4-9 1-5 0.450; *  9 * 4-9 1-5 0.450; * 10 * 4-9 1-5 0.450; * 11 * 4-9 1-5 0.450;"
+        "* 12 * 4-9 1-5 0.450; * 13 * 4-9 1-5 0.440; * 14 * 4-9 1-5 0.440; * 15 * 4-9 1-5 0.450;"
+        "* 16 * 4-9 1-5 0.470; * 17 * 4-9 1-5 0.510; * 18 * 4-9 1-5 0.540; * 19 * 4-9 1-5 0.560;"
+        "* 20 * 4-9 1-5 0.630; * 21 * 4-9 1-5 0.710; * 22 * 4-9 1-5 0.650; * 23 * 4-9 1-5 0.490"
+        "}"
+        "weekend-summer {"
+        "*  0 * 4-9 6-0 0.410; *  1 * 4-9 6-0 0.360; *  2 * 4-9 6-0 0.330; *  3 * 4-9 6-0 0.320;"
+        "*  4 * 4-9 6-0 0.320; *  5 * 4-9 6-0 0.320; *  6 * 4-9 6-0 0.340; *  7 * 4-9 6-0 0.390;"
+        "*  8 * 4-9 6-0 0.440; *  9 * 4-9 6-0 0.470; * 10 * 4-9 6-0 0.470; * 11 * 4-9 6-0 0.470;"
+        "* 12 * 4-9 6-0 0.470; * 13 * 4-9 6-0 0.460; * 14 * 4-9 6-0 0.460; * 15 * 4-9 6-0 0.460;"
+        "* 16 * 4-9 6-0 0.470; * 17 * 4-9 6-0 0.490; * 18 * 4-9 6-0 0.520; * 19 * 4-9 6-0 0.540;"
+        "* 20 * 4-9 6-0 0.610; * 21 * 4-9 6-0 0.680; * 22 * 4-9 6-0 0.630; * 23 * 4-9 6-0 0.500"
+        "}"
+        "weekday-winter {"
+        "*  0 * 10-3 1-5 0.4200; *  1 * 10-3 1-5 0.3800; *  2 * 10-3 1-5 0.3700; *  3 * 10-3 1-5 0.3600;"
+        "*  4 * 10-3 1-5 0.3700; *  5 * 10-3 1-5 0.4200; *  6 * 10-3 1-5 0.5800; *  7 * 10-3 1-5 0.6900;"
+        "*  8 * 10-3 1-5 0.6100; *  9 * 10-3 1-5 0.5600; * 10 * 10-3 1-5 0.5300; * 11 * 10-3 1-5 0.5100;"
+        "* 12 * 10-3 1-5 0.4900; * 13 * 10-3 1-5 0.4700; * 14 * 10-3 1-5 0.4700; * 15 * 10-3 1-5 0.5100;"
+        "* 16 * 10-3 1-5 0.6300; * 17 * 10-3 1-5 0.8400; * 18 * 10-3 1-5 0.9700; * 19 * 10-3 1-5 0.9800;"
+        "* 20 * 10-3 1-5 0.9600; * 21 * 10-3 1-5 0.8900; * 22 * 10-3 1-5 0.7400; * 23 * 10-3 1-5 0.5500"
+        "}"
+        "weekend-winter {"
+        "*  0 * 10-3 6-0 0.4900; *  1 * 10-3 6-0 0.4200; *  2 * 10-3 6-0 0.3800; *  3 * 10-3 6-0 0.3800;"
+        "*  4 * 10-3 6-0 0.3700; *  5 * 10-3 6-0 0.3800; *  6 * 10-3 6-0 0.4300; *  7 * 10-3 6-0 0.5100;"
+        "*  8 * 10-3 6-0 0.6000; *  9 * 10-3 6-0 0.6300; * 10 * 10-3 6-0 0.6300; * 11 * 10-3 6-0 0.6100;"
+        "* 12 * 10-3 6-0 0.6000; * 13 * 10-3 6-0 0.5900; * 14 * 10-3 6-0 0.5900; * 15 * 10-3 6-0 0.6100;"
+        "* 16 * 10-3 6-0 0.7100; * 17 * 10-3 6-0 0.8800; * 18 * 10-3 6-0 0.9600; * 19 * 10-3 6-0 0.9700;"
+        "* 20 * 10-3 6-0 0.9400; * 21 * 10-3 6-0 0.8800; * 22 * 10-3 6-0 0.7600; * 23 * 10-3 6-0 0.5800"
+        "}"
+        },
+
+{   "CLOTHESWASHER",
+        {20, false, {0.0,0.0,1.0}, 0.9, 1.0},
+        "type:analog; schedule: residential-clotheswasher-default; power: 0.5 kW",
+        "residential-clotheswasher-default",
+        "positive; nonzero; weekday-summer {"
+        "*  0 * 4-9 1-5 0.0029; *  1 * 4-9 1-5 0.0019; *  2 * 4-9 1-5 0.0014; *  3 * 4-9 1-5 0.0013;"
+        "*  4 * 4-9 1-5 0.0018; *  5 * 4-9 1-5 0.0026; *  6 * 4-9 1-5 0.0055; *  7 * 4-9 1-5 0.0126;"
+        "*  8 * 4-9 1-5 0.0181; *  9 * 4-9 1-5 0.0208; * 10 * 4-9 1-5 0.0229; * 11 * 4-9 1-5 0.0216;"
+        "* 12 * 4-9 1-5 0.0193; * 13 * 4-9 1-5 0.0170; * 14 * 4-9 1-5 0.0145; * 15 * 4-9 1-5 0.0135;"
+        "* 16 * 4-9 1-5 0.0135; * 17 * 4-9 1-5 0.0142; * 18 * 4-9 1-5 0.0145; * 19 * 4-9 1-5 0.0148;"
+        "* 20 * 4-9 1-5 0.0146; * 21 * 4-9 1-5 0.0141; * 22 * 4-9 1-5 0.0110; * 23 * 4-9 1-5 0.0062"
+        "}"
+        "weekend-summer {"
+        "*  0 * 4-9 6-0 0.0031; *  1 * 4-9 6-0 0.0019; *  2 * 4-9 6-0 0.0013; *  3 * 4-9 6-0 0.0012;"
+        "*  4 * 4-9 6-0 0.0012; *  5 * 4-9 6-0 0.0016; *  6 * 4-9 6-0 0.0027; *  7 * 4-9 6-0 0.0066;"
+        "*  8 * 4-9 6-0 0.0157; *  9 * 4-9 6-0 0.0220; * 10 * 4-9 6-0 0.0258; * 11 * 4-9 6-0 0.0251;"
+        "* 12 * 4-9 6-0 0.0231; * 13 * 4-9 6-0 0.0217; * 14 * 4-9 6-0 0.0186; * 15 * 4-9 6-0 0.0157;"
+        "* 16 * 4-9 6-0 0.0156; * 17 * 4-9 6-0 0.0151; * 18 * 4-9 6-0 0.0147; * 19 * 4-9 6-0 0.0150;"
+        "* 20 * 4-9 6-0 0.0156; * 21 * 4-9 6-0 0.0148; * 22 * 4-9 6-0 0.0106; * 23 * 4-9 6-0 0.0065"
+        "}"
+        "weekday-winter {"
+        "*  0 * 10-3 1-5 0.0036; *  1 * 10-3 1-5 0.0024; *  2 * 10-3 1-5 0.0020; *  3 * 10-3 1-5 0.0019;"
+        "*  4 * 10-3 1-5 0.0026; *  5 * 10-3 1-5 0.0040; *  6 * 10-3 1-5 0.0062; *  7 * 10-3 1-5 0.0118;"
+        "*  8 * 10-3 1-5 0.0177; *  9 * 10-3 1-5 0.0211; * 10 * 10-3 1-5 0.0215; * 11 * 10-3 1-5 0.0203;"
+        "* 12 * 10-3 1-5 0.0176; * 13 * 10-3 1-5 0.0155; * 14 * 10-3 1-5 0.0133; * 15 * 10-3 1-5 0.0130;"
+        "* 16 * 10-3 1-5 0.0145; * 17 * 10-3 1-5 0.0159; * 18 * 10-3 1-5 0.0166; * 19 * 10-3 1-5 0.0164;"
+        "* 20 * 10-3 1-5 0.0154; * 21 * 10-3 1-5 0.0149; * 22 * 10-3 1-5 0.0110; * 23 * 10-3 1-5 0.0065"
```

```
+       "}"
+       "weekend-winter {"
+       "*  0 * 10-3 6-0 0.0044; *  1 * 10-3 6-0 0.0030; *  2 * 10-3 6-0 0.0022; *  3 * 10-3 6-0 0.0020;"
+       "*  4 * 10-3 6-0 0.0021; *  5 * 10-3 6-0 0.0021; *  6 * 10-3 6-0 0.0030; *  7 * 10-3 6-0 0.0067;"
+       "*  8 * 10-3 6-0 0.0145; *  9 * 10-3 6-0 0.0244; * 10 * 10-3 6-0 0.0310; * 11 * 10-3 6-0 0.0323;"
+       "* 12 * 10-3 6-0 0.0308; * 13 * 10-3 6-0 0.0285; * 14 * 10-3 6-0 0.0251; * 15 * 10-3 6-0 0.0224;"
+       "* 16 * 10-3 6-0 0.0215; * 17 * 10-3 6-0 0.0203; * 18 * 10-3 6-0 0.0194; * 19 * 10-3 6-0 0.0188;"
+       "* 20 * 10-3 6-0 0.0180; * 21 * 10-3 6-0 0.0151; * 22 * 10-3 6-0 0.0122; * 23 * 10-3 6-0 0.0073"
+       "}"
+       },
+
+{   "WATERHEATER",
+       {30, true, {0.0,0.0,1.0}, 1.0, 0.5},
+       "type:analog; schedule: residential-waterheater-default; power: 0.56 kW",
+       "residential-waterheater-default",
+       "positive; nonzero; weekday-summer {"
+       "*  0 * 4-9 1-5 0.21; *  1 * 4-9 1-5 0.16; *  2 * 4-9 1-5 0.13; *  3 * 4-9 1-5 0.12;"
+       "*  4 * 4-9 1-5 0.15; *  5 * 4-9 1-5 0.26; *  6 * 4-9 1-5 0.51; *  7 * 4-9 1-5 0.76;"
+       "*  8 * 4-9 1-5 0.77; *  9 * 4-9 1-5 0.76; * 10 * 4-9 1-5 0.71; * 11 * 4-9 1-5 0.61;"
+       "* 12 * 4-9 1-5 0.54; * 13 * 4-9 1-5 0.49; * 14 * 4-9 1-5 0.43; * 15 * 4-9 1-5 0.41;"
+       "* 16 * 4-9 1-5 0.43; * 17 * 4-9 1-5 0.52; * 18 * 4-9 1-5 0.60; * 19 * 4-9 1-5 0.60;"
+       "* 20 * 4-9 1-5 0.59; * 21 * 4-9 1-5 0.60; * 22 * 4-9 1-5 0.55; * 23 * 4-9 1-5 0.37"
+       "}"
+       "weekend-summer {"
+       "*  0 * 4-9 6-0 0.23; *  1 * 4-9 6-0 0.17; *  2 * 4-9 6-0 0.14; *  3 * 4-9 6-0 0.13;"
+       "*  4 * 4-9 6-0 0.13; *  5 * 4-9 6-0 0.17; *  6 * 4-9 6-0 0.26; *  7 * 4-9 6-0 0.45;"
+       "*  8 * 4-9 6-0 0.69; *  9 * 4-9 6-0 0.85; * 10 * 4-9 6-0 0.84; * 11 * 4-9 6-0 0.76;"
+       "* 12 * 4-9 6-0 0.65; * 13 * 4-9 6-0 0.58; * 14 * 4-9 6-0 0.49; * 15 * 4-9 6-0 0.46;"
+       "* 16 * 4-9 6-0 0.46; * 17 * 4-9 6-0 0.50; * 18 * 4-9 6-0 0.54; * 19 * 4-9 6-0 0.55;"
+       "* 20 * 4-9 6-0 0.56; * 21 * 4-9 6-0 0.56; * 22 * 4-9 6-0 0.49; * 23 * 4-9 6-0 0.38"
+       "}"
+       "weekday-winter {"
+       "*  0 * 10-3 1-5 0.25; *  1 * 10-3 1-5 0.19; *  2 * 10-3 1-5 0.16; *  3 * 10-3 1-5 0.15;"
+       "*  4 * 10-3 1-5 0.18; *  5 * 10-3 1-5 0.34; *  6 * 10-3 1-5 0.74; *  7 * 10-3 1-5 1.20;"
+       "*  8 * 10-3 1-5 1.10; *  9 * 10-3 1-5 0.94; * 10 * 10-3 1-5 0.82; * 11 * 10-3 1-5 0.71;"
+       "* 12 * 10-3 1-5 0.62; * 13 * 10-3 1-5 0.55; * 14 * 10-3 1-5 0.48; * 15 * 10-3 1-5 0.47;"
+       "* 16 * 10-3 1-5 0.54; * 17 * 10-3 1-5 0.68; * 18 * 10-3 1-5 0.83; * 19 * 10-3 1-5 0.82;"
+       "* 20 * 10-3 1-5 0.74; * 21 * 10-3 1-5 0.68; * 22 * 10-3 1-5 0.57; * 23 * 10-3 1-5 0.40"
+       "}"
+       "weekend-winter {"
+       "*  0 * 10-3 6-0 0.29; *  1 * 10-3 6-0 0.22; *  2 * 10-3 6-0 0.17; *  3 * 10-3 6-0 0.15;"
+       "*  4 * 10-3 6-0 0.16; *  5 * 10-3 6-0 0.19; *  6 * 10-3 6-0 0.27; *  7 * 10-3 6-0 0.47;"
+       "*  8 * 10-3 6-0 0.82; *  9 * 10-3 6-0 1.08; * 10 * 10-3 6-0 1.15; * 11 * 10-3 6-0 1.08;"
+       "* 12 * 10-3 6-0 0.98; * 13 * 10-3 6-0 0.87; * 14 * 10-3 6-0 0.77; * 15 * 10-3 6-0 0.69;"
+       "* 16 * 10-3 6-0 0.72; * 17 * 10-3 6-0 0.78; * 18 * 10-3 6-0 0.83; * 19 * 10-3 6-0 0.79;"
+       "* 20 * 10-3 6-0 0.72; * 21 * 10-3 6-0 0.64; * 22 * 10-3 6-0 0.53; * 23 * 10-3 6-0 0.43"
+       "}"
+       },
+
+{   "REFRIGERATOR",
+       {20, false, {0.1,0.0,0.9}, 0.9, 1.0},
+       "type:analog; schedule: residential-refrigerator-default; power: 0.43 kW",
+       "residential-refrigerator-default",
+       "positive; nonzero; weekday-summer {"
+       "*  0 * 4-9 1-5 0.187; *  1 * 4-9 1-5 0.182; *  2 * 4-9 1-5 0.176; *  3 * 4-9 1-5 0.170;"
+       "*  4 * 4-9 1-5 0.168; *  5 * 4-9 1-5 0.168; *  6 * 4-9 1-5 0.177; *  7 * 4-9 1-5 0.174;"
+       "*  8 * 4-9 1-5 0.177; *  9 * 4-9 1-5 0.180; * 10 * 4-9 1-5 0.180; * 11 * 4-9 1-5 0.183;"
+       "* 12 * 4-9 1-5 0.192; * 13 * 4-9 1-5 0.192; * 14 * 4-9 1-5 0.194; * 15 * 4-9 1-5 0.196;"
+       "* 16 * 4-9 1-5 0.205; * 17 * 4-9 1-5 0.217; * 18 * 4-9 1-5 0.225; * 19 * 4-9 1-5 0.221;"
+       "* 20 * 4-9 1-5 0.216; * 21 * 4-9 1-5 0.214; * 22 * 4-9 1-5 0.207; * 23 * 4-9 1-5 0.195"
+       "}"
+       "weekend-summer {"
+       "*  0 * 4-9 6-0 0.187; *  1 * 4-9 6-0 0.181; *  2 * 4-9 6-0 0.176; *  3 * 4-9 6-0 0.169;"
+       "*  4 * 4-9 6-0 0.166; *  5 * 4-9 6-0 0.164; *  6 * 4-9 6-0 0.167; *  7 * 4-9 6-0 0.169;"
+       "*  8 * 4-9 6-0 0.180; *  9 * 4-9 6-0 0.184; * 10 * 4-9 6-0 0.187; * 11 * 4-9 6-0 0.187;"
+       "* 12 * 4-9 6-0 0.195; * 13 * 4-9 6-0 0.200; * 14 * 4-9 6-0 0.201; * 15 * 4-9 6-0 0.203;"
+       "* 16 * 4-9 6-0 0.209; * 17 * 4-9 6-0 0.218; * 18 * 4-9 6-0 0.222; * 19 * 4-9 6-0 0.221;"
+       "* 20 * 4-9 6-0 0.217; * 21 * 4-9 6-0 0.216; * 22 * 4-9 6-0 0.207; * 23 * 4-9 6-0 0.196"
+       "}"
+       "weekday-winter {"
+       "*  0 * 10-3 1-5 0.1530; *  1 * 10-3 1-5 0.1500; *  2 * 10-3 1-5 0.1460; *  3 * 10-3 1-5 0.1420;"
+       "*  4 * 10-3 1-5 0.1400; *  5 * 10-3 1-5 0.1450; *  6 * 10-3 1-5 0.1520; *  7 * 10-3 1-5 0.1600;"
+       "*  8 * 10-3 1-5 0.1580; *  9 * 10-3 1-5 0.1580; * 10 * 10-3 1-5 0.1560; * 11 * 10-3 1-5 0.1560;"
+       "* 12 * 10-3 1-5 0.1630; * 13 * 10-3 1-5 0.1620; * 14 * 10-3 1-5 0.1590; * 15 * 10-3 1-5 0.1620;"
+       "* 16 * 10-3 1-5 0.1690; * 17 * 10-3 1-5 0.1850; * 18 * 10-3 1-5 0.1920; * 19 * 10-3 1-5 0.1820;"
+       "* 20 * 10-3 1-5 0.1800; * 21 * 10-3 1-5 0.1760; * 22 * 10-3 1-5 0.1670; * 23 * 10-3 1-5 0.1590"
+       "}"
+       "weekend-winter {"
+       "*  0 * 10-3 6-0 0.1560; *  1 * 10-3 6-0 0.1520; *  2 * 10-3 6-0 0.1470; *  3 * 10-3 6-0 0.1430;"
+       "*  4 * 10-3 6-0 0.1420; *  5 * 10-3 6-0 0.1430; *  6 * 10-3 6-0 0.1430; *  7 * 10-3 6-0 0.1500;"
+       "*  8 * 10-3 6-0 0.1610; *  9 * 10-3 6-0 0.1690; * 10 * 10-3 6-0 0.1670; * 11 * 10-3 6-0 0.1660;"
+       "* 12 * 10-3 6-0 0.1740; * 13 * 10-3 6-0 0.1760; * 14 * 10-3 6-0 0.1740; * 15 * 10-3 6-0 0.1750;"
+       "* 16 * 10-3 6-0 0.1790; * 17 * 10-3 6-0 0.1910; * 18 * 10-3 6-0 0.1930; * 19 * 10-3 6-0 0.1870;"
+       "* 20 * 10-3 6-0 0.1840; * 21 * 10-3 6-0 0.1780; * 22 * 10-3 6-0 0.1700; * 23 * 10-3 6-0 0.1600"
+       "}"
+       },
+
+{   "DRYER",
+       {30, true, {0.9,0.0,0.1}, 0.99, 0.15},
```

```
+        "type:analog; schedule: residential-dryer-default; power: 0.64 kW",
+        "residential-dryer-default",
+        "positive; nonzero; weekday-summer {"
+        "*  0 * 4-9 1-5 0.036; *  1 * 4-9 1-5 0.013; *  2 * 4-9 1-5 0.007; *  3 * 4-9 1-5 0.005;"
+        "*  4 * 4-9 1-5 0.005; *  5 * 4-9 1-5 0.017; *  6 * 4-9 1-5 0.048; *  7 * 4-9 1-5 0.085;"
+        "*  8 * 4-9 1-5 0.115; *  9 * 4-9 1-5 0.156; * 10 * 4-9 1-5 0.179; * 11 * 4-9 1-5 0.185;"
+        "* 12 * 4-9 1-5 0.172; * 13 * 4-9 1-5 0.162; * 14 * 4-9 1-5 0.145; * 15 * 4-9 1-5 0.136;"
+        "* 16 * 4-9 1-5 0.133; * 17 * 4-9 1-5 0.134; * 18 * 4-9 1-5 0.127; * 19 * 4-9 1-5 0.130;"
+        "* 20 * 4-9 1-5 0.141; * 21 * 4-9 1-5 0.154; * 22 * 4-9 1-5 0.138; * 23 * 4-9 1-5 0.083"
+        "}"
+        "weekend-summer {"
+        "*  0 * 4-9 6-0 0.041; *  1 * 4-9 6-0 0.017; *  2 * 4-9 6-0 0.008; *  3 * 4-9 6-0 0.005;"
+        "*  4 * 4-9 6-0 0.005; *  5 * 4-9 6-0 0.007; *  6 * 4-9 6-0 0.018; *  7 * 4-9 6-0 0.047;"
+        "*  8 * 4-9 6-0 0.100; *  9 * 4-9 6-0 0.168; * 10 * 4-9 6-0 0.205; * 11 * 4-9 6-0 0.220;"
+        "* 12 * 4-9 6-0 0.211; * 13 * 4-9 6-0 0.210; * 14 * 4-9 6-0 0.188; * 15 * 4-9 6-0 0.168;"
+        "* 16 * 4-9 6-0 0.154; * 17 * 4-9 6-0 0.146; * 18 * 4-9 6-0 0.138; * 19 * 4-9 6-0 0.137;"
+        "* 20 * 4-9 6-0 0.144; * 21 * 4-9 6-0 0.155; * 22 * 4-9 6-0 0.131; * 23 * 4-9 6-0 0.081"
+        "}"
+        "weekday-winter {"
+        "*  0 * 10-3 1-5 0.0360; *  1 * 10-3 1-5 0.0160; *  2 * 10-3 1-5 0.0100; *  3 * 10-3 1-5 0.0070;"
+        "*  4 * 10-3 1-5 0.0090; *  5 * 10-3 1-5 0.0230; *  6 * 10-3 1-5 0.0610; *  7 * 10-3 1-5 0.1030;"
+        "*  8 * 10-3 1-5 0.1320; *  9 * 10-3 1-5 0.1750; * 10 * 10-3 1-5 0.2050; * 11 * 10-3 1-5 0.2130;"
+        "* 12 * 10-3 1-5 0.1940; * 13 * 10-3 1-5 0.1770; * 14 * 10-3 1-5 0.1610; * 15 * 10-3 1-5 0.1560;"
+        "* 16 * 10-3 1-5 0.1640; * 17 * 10-3 1-5 0.1710; * 18 * 10-3 1-5 0.1610; * 19 * 10-3 1-5 0.1590;"
+        "* 20 * 10-3 1-5 0.1670; * 21 * 10-3 1-5 0.1690; * 22 * 10-3 1-5 0.1380; * 23 * 10-3 1-5 0.0820"
+        "}"
+        "weekend-winter {"
+        "*  0 * 10-3 6-0 0.0390; *  1 * 10-3 6-0 0.0190; *  2 * 10-3 6-0 0.0110; *  3 * 10-3 6-0 0.0070;"
+        "*  4 * 10-3 6-0 0.0080; *  5 * 10-3 6-0 0.0090; *  6 * 10-3 6-0 0.0160; *  7 * 10-3 6-0 0.0430;"
+        "*  8 * 10-3 6-0 0.1010; *  9 * 10-3 6-0 0.1810; * 10 * 10-3 6-0 0.2640; * 11 * 10-3 6-0 0.3050;"
+        "* 12 * 10-3 6-0 0.3110; * 13 * 10-3 6-0 0.3060; * 14 * 10-3 6-0 0.2850; * 15 * 10-3 6-0 0.2700;"
+        "* 16 * 10-3 6-0 0.2600; * 17 * 10-3 6-0 0.2450; * 18 * 10-3 6-0 0.2200; * 19 * 10-3 6-0 0.1980;"
+        "* 20 * 10-3 6-0 0.1880; * 21 * 10-3 6-0 0.1790; * 22 * 10-3 6-0 0.1480; * 23 * 10-3 6-0 0.0930"
+        "}"
+        },
+
+{    "FREEZER",
+        {20, false, {0.1,0.0,0.9}, 0.9, 1.0},
+        "type:analog; schedule: residential-freezer-default; power: 0.38 kW",
+        "residential-freezer-default",
+        "positive; nonzero; weekday-summer {"
+        "*  0 * 4-9 1-5 0.210; *  1 * 4-9 1-5 0.213; *  2 * 4-9 1-5 0.208; *  3 * 4-9 1-5 0.202;"
+        "*  4 * 4-9 1-5 0.203; *  5 * 4-9 1-5 0.198; *  6 * 4-9 1-5 0.190; *  7 * 4-9 1-5 0.186;"
+        "*  8 * 4-9 1-5 0.189; *  9 * 4-9 1-5 0.194; * 10 * 4-9 1-5 0.199; * 11 * 4-9 1-5 0.202;"
+        "* 12 * 4-9 1-5 0.211; * 13 * 4-9 1-5 0.214; * 14 * 4-9 1-5 0.219; * 15 * 4-9 1-5 0.222;"
+        "* 16 * 4-9 1-5 0.230; * 17 * 4-9 1-5 0.228; * 18 * 4-9 1-5 0.229; * 19 * 4-9 1-5 0.223;"
+        "* 20 * 4-9 1-5 0.224; * 21 * 4-9 1-5 0.223; * 22 * 4-9 1-5 0.218; * 23 * 4-9 1-5 0.214"
+        "}"
+        "weekend-summer {"
+        "*  0 * 4-9 6-0 0.203; *  1 * 4-9 6-0 0.202; *  2 * 4-9 6-0 0.202; *  3 * 4-9 6-0 0.193;"
+        "*  4 * 4-9 6-0 0.198; *  5 * 4-9 6-0 0.195; *  6 * 4-9 6-0 0.191; *  7 * 4-9 6-0 0.183;"
+        "*  8 * 4-9 6-0 0.184; *  9 * 4-9 6-0 0.192; * 10 * 4-9 6-0 0.197; * 11 * 4-9 6-0 0.202;"
+        "* 12 * 4-9 6-0 0.208; * 13 * 4-9 6-0 0.219; * 14 * 4-9 6-0 0.219; * 15 * 4-9 6-0 0.225;"
+        "* 16 * 4-9 6-0 0.225; * 17 * 4-9 6-0 0.225; * 18 * 4-9 6-0 0.223; * 19 * 4-9 6-0 0.219;"
+        "* 20 * 4-9 6-0 0.221; * 21 * 4-9 6-0 0.220; * 22 * 4-9 6-0 0.215; * 23 * 4-9 6-0 0.209"
+        "}"
+        "weekday-winter {"
+        "*  0 * 10-3 1-5 0.149; *  1 * 10-3 1-5 0.148; *  2 * 10-3 1-5 0.145; *  3 * 10-3 1-5 0.144;"
+        "*  4 * 10-3 1-5 0.143; *  5 * 10-3 1-5 0.140; *  6 * 10-3 1-5 0.138; *  7 * 10-3 1-5 0.138;"
+        "*  8 * 10-3 1-5 0.140; *  9 * 10-3 1-5 0.141; * 10 * 10-3 1-5 0.142; * 11 * 10-3 1-5 0.147;"
+        "* 12 * 10-3 1-5 0.153; * 13 * 10-3 1-5 0.154; * 14 * 10-3 1-5 0.152; * 15 * 10-3 1-5 0.151;"
+        "* 16 * 10-3 1-5 0.161; * 17 * 10-3 1-5 0.174; * 18 * 10-3 1-5 0.176; * 19 * 10-3 1-5 0.176;"
+        "* 20 * 10-3 1-5 0.175; * 21 * 10-3 1-5 0.169; * 22 * 10-3 1-5 0.160; * 23 * 10-3 1-5 0.153"
+        "}"
+        "weekend-winter {"
+        "*  0 * 10-3 6-0 0.155; *  1 * 10-3 6-0 0.150; *  2 * 10-3 6-0 0.143; *  3 * 10-3 6-0 0.141;"
+        "*  4 * 10-3 6-0 0.141; *  5 * 10-3 6-0 0.139; *  6 * 10-3 6-0 0.138; *  7 * 10-3 6-0 0.139;"
+        "*  8 * 10-3 6-0 0.142; *  9 * 10-3 6-0 0.142; * 10 * 10-3 6-0 0.145; * 11 * 10-3 6-0 0.153;"
+        "* 12 * 10-3 6-0 0.161; * 13 * 10-3 6-0 0.162; * 14 * 10-3 6-0 0.160; * 15 * 10-3 6-0 0.161;"
+        "* 16 * 10-3 6-0 0.165; * 17 * 10-3 6-0 0.177; * 18 * 10-3 6-0 0.179; * 19 * 10-3 6-0 0.177;"
+        "* 20 * 10-3 6-0 0.171; * 21 * 10-3 6-0 0.168; * 22 * 10-3 6-0 0.160; * 23 * 10-3 6-0 0.151"
+        "}"
+        },
+{    "DISHWASHER",
+        {20, false, {0.8,0,0.2}, 0.98, 1.0},
+        "type:analog; schedule: residential-dishwasher-default; power: 1.8 kW",
+        "residential-dishwasher-default",
+        "normal; positive; nonzero; weekday-summer {"
+        "*  0 * 4-9 1-5 0.0068; *  1 * 4-9 1-5 0.0029; *  2 * 4-9 1-5 0.0016; *  3 * 4-9 1-5 0.0013;"
+        "*  4 * 4-9 1-5 0.0012; *  5 * 4-9 1-5 0.0037; *  6 * 4-9 1-5 0.0075; *  7 * 4-9 1-5 0.0129;"
+        "*  8 * 4-9 1-5 0.0180; *  9 * 4-9 1-5 0.0177; * 10 * 4-9 1-5 0.0144; * 11 * 4-9 1-5 0.0113;"
+        "* 12 * 4-9 1-5 0.0116; * 13 * 4-9 1-5 0.0128; * 14 * 4-9 1-5 0.0109; * 15 * 4-9 1-5 0.0105;"
+        "* 16 * 4-9 1-5 0.0124; * 17 * 4-9 1-5 0.0156; * 18 * 4-9 1-5 0.0278; * 19 * 4-9 1-5 0.0343;"
+        "* 20 * 4-9 1-5 0.0279; * 21 * 4-9 1-5 0.0234; * 22 * 4-9 1-5 0.0194; * 23 * 4-9 1-5 0.0131"
+        "}"
+        "weekend-summer {"
+        "*  0 * 4-9 6-0 0.0093; *  1 * 4-9 6-0 0.0045; *  2 * 4-9 6-0 0.0021; *  3 * 4-9 6-0 0.0015;"
+        "*  4 * 4-9 6-0 0.0013; *  5 * 4-9 6-0 0.0015; *  6 * 4-9 6-0 0.0026; *  7 * 4-9 6-0 0.0067;"
+        "*  8 * 4-9 6-0 0.0142; *  9 * 4-9 6-0 0.0221; * 10 * 4-9 6-0 0.0259; * 11 * 4-9 6-0 0.0238;"
```

```
+        "* 12 * 4-9 6-0 0.0214; * 13 * 4-9 6-0 0.0214; * 14 * 4-9 6-0 0.0188; * 15 * 4-9 6-0 0.0169;"
+        "* 16 * 4-9 6-0 0.0156; * 17 * 4-9 6-0 0.0166; * 18 * 4-9 6-0 0.0249; * 19 * 4-9 6-0 0.0298;"
+        "* 20 * 4-9 6-0 0.0267; * 21 * 4-9 6-0 0.0221; * 22 * 4-9 6-0 0.0174; * 23 * 4-9 6-0 0.0145"
+        "}"
+        "weekday-winter {"
+        "*  0 * 10-3 1-5 0.0068; *  1 * 10-3 1-5 0.0029; *  2 * 10-3 1-5 0.0016; *  3 * 10-3 1-5 0.0013;"
+        "*  4 * 10-3 1-5 0.0012; *  5 * 10-3 1-5 0.0037; *  6 * 10-3 1-5 0.0075; *  7 * 10-3 1-5 0.0129;"
+        "*  8 * 10-3 1-5 0.0180; *  9 * 10-3 1-5 0.0177; * 10 * 10-3 1-5 0.0144; * 11 * 10-3 1-5 0.0113;"
+        "* 12 * 10-3 1-5 0.0116; * 13 * 10-3 1-5 0.0128; * 14 * 10-3 1-5 0.0109; * 15 * 10-3 1-5 0.0105;"
+        "* 16 * 10-3 1-5 0.0124; * 17 * 10-3 1-5 0.0156; * 18 * 10-3 1-5 0.0278; * 19 * 10-3 1-5 0.0343;"
+        "* 20 * 10-3 1-5 0.0279; * 21 * 10-3 1-5 0.0234; * 22 * 10-3 1-5 0.0194; * 23 * 10-3 1-5 0.0131"
+        "}"
+        "weekend-winter {"
+        "*  0 * 10-3 6-0 0.0093; *  1 * 10-3 6-0 0.0045; *  2 * 10-3 6-0 0.0021; *  3 * 10-3 6-0 0.0015;"
+        "*  4 * 10-3 6-0 0.0013; *  5 * 10-3 6-0 0.0015; *  6 * 10-3 6-0 0.0026; *  7 * 10-3 6-0 0.0067;"
+        "*  8 * 10-3 6-0 0.0142; *  9 * 10-3 6-0 0.0221; * 10 * 10-3 6-0 0.0259; * 11 * 10-3 6-0 0.0238;"
+        "* 12 * 10-3 6-0 0.0214; * 13 * 10-3 6-0 0.0214; * 14 * 10-3 6-0 0.0188; * 15 * 10-3 6-0 0.0169;"
+        "* 16 * 10-3 6-0 0.0156; * 17 * 10-3 6-0 0.0166; * 18 * 10-3 6-0 0.0249; * 19 * 10-3 6-0 0.0298;"
+        "* 20 * 10-3 6-0 0.0267; * 21 * 10-3 6-0 0.0221; * 22 * 10-3 6-0 0.0174; * 23 * 10-3 6-0 0.0145"
+        "}"
+},
+{   "RANGE",
+        {40, true, {1,0,0}, 0.85, 0.8},
+        "type:analog; schedule: residential-range-default; power: 0.56 kW", // no data
+        "residential-range-default",
+        "positive; nonzero; weekday-summer {"
+        "*  0 * 4-9 1-5 0.009; *  1 * 4-9 1-5 0.008; *  2 * 4-9 1-5 0.007; *  3 * 4-9 1-5 0.007;"
+        "*  4 * 4-9 1-5 0.008; *  5 * 4-9 1-5 0.012; *  6 * 4-9 1-5 0.025; *  7 * 4-9 1-5 0.040;"
+        "*  8 * 4-9 1-5 0.044; *  9 * 4-9 1-5 0.042; * 10 * 4-9 1-5 0.042; * 11 * 4-9 1-5 0.053;"
+        "* 12 * 4-9 1-5 0.057; * 13 * 4-9 1-5 0.046; * 14 * 4-9 1-5 0.044; * 15 * 4-9 1-5 0.053;"
+        "* 16 * 4-9 1-5 0.094; * 17 * 4-9 1-5 0.168; * 18 * 4-9 1-5 0.148; * 19 * 4-9 1-5 0.086;"
+        "* 20 * 4-9 1-5 0.053; * 21 * 4-9 1-5 0.038; * 22 * 4-9 1-5 0.023; * 23 * 4-9 1-5 0.013"
+        "}"
+        "weekend-summer {"
+        "*  0 * 4-9 6-0 0.009; *  1 * 4-9 6-0 0.007; *  2 * 4-9 6-0 0.007; *  3 * 4-9 6-0 0.007;"
+        "*  4 * 4-9 6-0 0.007; *  5 * 4-9 6-0 0.009; *  6 * 4-9 6-0 0.017; *  7 * 4-9 6-0 0.038;"
+        "*  8 * 4-9 6-0 0.060; *  9 * 4-9 6-0 0.068; * 10 * 4-9 6-0 0.065; * 11 * 4-9 6-0 0.067;"
+        "* 12 * 4-9 6-0 0.076; * 13 * 4-9 6-0 0.066; * 14 * 4-9 6-0 0.061; * 15 * 4-9 6-0 0.067;"
+        "* 16 * 4-9 6-0 0.091; * 17 * 4-9 6-0 0.134; * 18 * 4-9 6-0 0.121; * 19 * 4-9 6-0 0.080;"
+        "* 20 * 4-9 6-0 0.052; * 21 * 4-9 6-0 0.035; * 22 * 4-9 6-0 0.022; * 23 * 4-9 6-0 0.011"
+        "}"
+        "weekday-winter {"
+        "*  0 * 10-3 1-5 0.010; *  1 * 10-3 1-5 0.009; *  2 * 10-3 1-5 0.009; *  3 * 10-3 1-5 0.009;"
+        "*  4 * 10-3 1-5 0.009; *  5 * 10-3 1-5 0.016; *  6 * 10-3 1-5 0.032; *  7 * 10-3 1-5 0.050;"
+        "*  8 * 10-3 1-5 0.045; *  9 * 10-3 1-5 0.043; * 10 * 10-3 1-5 0.045; * 11 * 10-3 1-5 0.059;"
+        "* 12 * 10-3 1-5 0.063; * 13 * 10-3 1-5 0.053; * 14 * 10-3 1-5 0.052; * 15 * 10-3 1-5 0.072;"
+        "* 16 * 10-3 1-5 0.138; * 17 * 10-3 1-5 0.242; * 18 * 10-3 1-5 0.182; * 19 * 10-3 1-5 0.088;"
+        "* 20 * 10-3 1-5 0.051; * 21 * 10-3 1-5 0.034; * 22 * 10-3 1-5 0.022; * 23 * 10-3 1-5 0.014"
+        "}"
+        "weekend-winter {"
+        "*  0 * 10-3 6-0 0.013; *  1 * 10-3 6-0 0.010; *  2 * 10-3 6-0 0.010; *  3 * 10-3 6-0 0.010;"
+        "*  4 * 10-3 6-0 0.010; *  5 * 10-3 6-0 0.012; *  6 * 10-3 6-0 0.018; *  7 * 10-3 6-0 0.040;"
+        "*  8 * 10-3 6-0 0.073; *  9 * 10-3 6-0 0.094; * 10 * 10-3 6-0 0.091; * 11 * 10-3 6-0 0.100;"
+        "* 12 * 10-3 6-0 0.117; * 13 * 10-3 6-0 0.109; * 14 * 10-3 6-0 0.100; * 15 * 10-3 6-0 0.108;"
+        "* 16 * 10-3 6-0 0.153; * 17 * 10-3 6-0 0.215; * 18 * 10-3 6-0 0.161; * 19 * 10-3 6-0 0.085;"
+        "* 20 * 10-3 6-0 0.050; * 21 * 10-3 6-0 0.033; * 22 * 10-3 6-0 0.022; * 23 * 10-3 6-0 0.014"
+        "}"
+},
+{   "MICROWAVE",
+        {40, false, {0,0,1}, 0.7, 0.8},
+        "type:analog; schedule: residential-microwave-default; power: 0.12 kW", // 20% of range
+        "residential-microwave-default",
+        "positive; nonzero; weekday-summer {"
+        "*  0 * 4-9 1-5 0.009; *  1 * 4-9 1-5 0.008; *  2 * 4-9 1-5 0.007; *  3 * 4-9 1-5 0.007;"
+        "*  4 * 4-9 1-5 0.008; *  5 * 4-9 1-5 0.012; *  6 * 4-9 1-5 0.025; *  7 * 4-9 1-5 0.040;"
+        "*  8 * 4-9 1-5 0.044; *  9 * 4-9 1-5 0.042; * 10 * 4-9 1-5 0.042; * 11 * 4-9 1-5 0.053;"
+        "* 12 * 4-9 1-5 0.057; * 13 * 4-9 1-5 0.046; * 14 * 4-9 1-5 0.044; * 15 * 4-9 1-5 0.053;"
+        "* 16 * 4-9 1-5 0.094; * 17 * 4-9 1-5 0.168; * 18 * 4-9 1-5 0.148; * 19 * 4-9 1-5 0.086;"
+        "* 20 * 4-9 1-5 0.053; * 21 * 4-9 1-5 0.038; * 22 * 4-9 1-5 0.023; * 23 * 4-9 1-5 0.013"
+        "}"
+        "weekend-summer {"
+        "*  0 * 4-9 6-0 0.009; *  1 * 4-9 6-0 0.007; *  2 * 4-9 6-0 0.007; *  3 * 4-9 6-0 0.007;"
+        "*  4 * 4-9 6-0 0.007; *  5 * 4-9 6-0 0.009; *  6 * 4-9 6-0 0.017; *  7 * 4-9 6-0 0.038;"
+        "*  8 * 4-9 6-0 0.060; *  9 * 4-9 6-0 0.068; * 10 * 4-9 6-0 0.065; * 11 * 4-9 6-0 0.067;"
+        "* 12 * 4-9 6-0 0.076; * 13 * 4-9 6-0 0.066; * 14 * 4-9 6-0 0.061; * 15 * 4-9 6-0 0.067;"
+        "* 16 * 4-9 6-0 0.091; * 17 * 4-9 6-0 0.134; * 18 * 4-9 6-0 0.121; * 19 * 4-9 6-0 0.080;"
+        "* 20 * 4-9 6-0 0.052; * 21 * 4-9 6-0 0.035; * 22 * 4-9 6-0 0.022; * 23 * 4-9 6-0 0.011"
+        "}"
+        "weekday-winter {"
+        "*  0 * 10-3 1-5 0.010; *  1 * 10-3 1-5 0.009; *  2 * 10-3 1-5 0.009; *  3 * 10-3 1-5 0.009;"
+        "*  4 * 10-3 1-5 0.009; *  5 * 10-3 1-5 0.016; *  6 * 10-3 1-5 0.032; *  7 * 10-3 1-5 0.050;"
+        "*  8 * 10-3 1-5 0.045; *  9 * 10-3 1-5 0.043; * 10 * 10-3 1-5 0.045; * 11 * 10-3 1-5 0.059;"
+        "* 12 * 10-3 1-5 0.063; * 13 * 10-3 1-5 0.053; * 14 * 10-3 1-5 0.052; * 15 * 10-3 1-5 0.072;"
+        "* 16 * 10-3 1-5 0.138; * 17 * 10-3 1-5 0.242; * 18 * 10-3 1-5 0.182; * 19 * 10-3 1-5 0.088;"
+        "* 20 * 10-3 1-5 0.051; * 21 * 10-3 1-5 0.034; * 22 * 10-3 1-5 0.022; * 23 * 10-3 1-5 0.014"
+        "}"
+        "weekend-winter {"
+        "*  0 * 10-3 6-0 0.013; *  1 * 10-3 6-0 0.010; *  2 * 10-3 6-0 0.010; *  3 * 10-3 6-0 0.010;"
+        "*  4 * 10-3 6-0 0.010; *  5 * 10-3 6-0 0.012; *  6 * 10-3 6-0 0.018; *  7 * 10-3 6-0 0.040;"
```

```
+       "*  8 * 10-3 6-0 0.073; *  9 * 10-3 6-0 0.094; * 10 * 10-3 6-0 0.091; * 11 * 10-3 6-0 0.100;"
+       "* 12 * 10-3 6-0 0.117; * 13 * 10-3 6-0 0.109; * 14 * 10-3 6-0 0.100; * 15 * 10-3 6-0 0.108;"
+       "* 16 * 10-3 6-0 0.153; * 17 * 10-3 6-0 0.215; * 18 * 10-3 6-0 0.161; * 19 * 10-3 6-0 0.085;"
+       "* 20 * 10-3 6-0 0.050; * 21 * 10-3 6-0 0.033; * 22 * 10-3 6-0 0.022; * 23 * 10-3 6-0 0.014"
+       "}"
+},
+
+/// @todo add other implicit enduse schedules and shapes as they are defined
Index: residential/house_e.cpp
===================================================================
--- residential/house_e.cpp     (revision 4854)
+++ residential/house_e.cpp     (working copy)
@@ -122,385 +122,7 @@
        char *schedule_definition;
 } implicit_enduse_data[] =
 {
-       // lighting (source: ELCAP lit-sp.dat)
-       {       "LIGHTS",
-               {30, false, {0.5,0.1,0.4}, 0.97, 0.9},
-               "type:analog; schedule: residential-lights-default; power: 0.76 kW",
-               "residential-lights-default",
-               "positive; nonzero; weekday-summer {"
-               "*  0 * 4-9 1-5 0.380; *  1 * 4-9 1-5 0.340; *  2 * 4-9 1-5 0.320; *  3 * 4-9 1-5 0.320;"
-               "*  4 * 4-9 1-5 0.320; *  5 * 4-9 1-5 0.350; *  6 * 4-9 1-5 0.410; *  7 * 4-9 1-5 0.450;"
-               "*  8 * 4-9 1-5 0.450; *  9 * 4-9 1-5 0.450; * 10 * 4-9 1-5 0.450; * 11 * 4-9 1-5 0.450;"
-               "* 12 * 4-9 1-5 0.450; * 13 * 4-9 1-5 0.440; * 14 * 4-9 1-5 0.440; * 15 * 4-9 1-5 0.450;"
-               "* 16 * 4-9 1-5 0.470; * 17 * 4-9 1-5 0.510; * 18 * 4-9 1-5 0.540; * 19 * 4-9 1-5 0.560;"
-               "* 20 * 4-9 1-5 0.630; * 21 * 4-9 1-5 0.710; * 22 * 4-9 1-5 0.650; * 23 * 4-9 1-5 0.490"
-               "}"
-               "weekend-summer {"
-               "*  0 * 4-9 6-0 0.410; *  1 * 4-9 6-0 0.360; *  2 * 4-9 6-0 0.330; *  3 * 4-9 6-0 0.320;"
-               "*  4 * 4-9 6-0 0.320; *  5 * 4-9 6-0 0.320; *  6 * 4-9 6-0 0.340; *  7 * 4-9 6-0 0.390;"
-               "*  8 * 4-9 6-0 0.440; *  9 * 4-9 6-0 0.470; * 10 * 4-9 6-0 0.470; * 11 * 4-9 6-0 0.470;"
-               "* 12 * 4-9 6-0 0.470; * 13 * 4-9 6-0 0.460; * 14 * 4-9 6-0 0.460; * 15 * 4-9 6-0 0.460;"
-               "* 16 * 4-9 6-0 0.470; * 17 * 4-9 6-0 0.490; * 18 * 4-9 6-0 0.520; * 19 * 4-9 6-0 0.540;"
-               "* 20 * 4-9 6-0 0.610; * 21 * 4-9 6-0 0.680; * 22 * 4-9 6-0 0.630; * 23 * 4-9 6-0 0.500"
-               "}"
-               "weekday-winter {"
-               "*  0 * 10-3 1-5 0.4200; *  1 * 10-3 1-5 0.3800; *  2 * 10-3 1-5 0.3700; *  3 * 10-3 1-5 0.3600;"
-               "*  4 * 10-3 1-5 0.3700; *  5 * 10-3 1-5 0.4200; *  6 * 10-3 1-5 0.5800; *  7 * 10-3 1-5 0.6900;"
-               "*  8 * 10-3 1-5 0.6100; *  9 * 10-3 1-5 0.5600; * 10 * 10-3 1-5 0.5300; * 11 * 10-3 1-5 0.5100;"
-               "* 12 * 10-3 1-5 0.4900; * 13 * 10-3 1-5 0.4700; * 14 * 10-3 1-5 0.4700; * 15 * 10-3 1-5 0.5100;"
-               "* 16 * 10-3 1-5 0.6300; * 17 * 10-3 1-5 0.8400; * 18 * 10-3 1-5 0.9700; * 19 * 10-3 1-5 0.9800;"
-               "* 20 * 10-3 1-5 0.9600; * 21 * 10-3 1-5 0.8900; * 22 * 10-3 1-5 0.7400; * 23 * 10-3 1-5 0.5500"
-               "}"
-               "weekend-winter {"
-               "*  0 * 10-3 6-0 0.4900; *  1 * 10-3 6-0 0.4200; *  2 * 10-3 6-0 0.3800; *  3 * 10-3 6-0 0.3800;"
-               "*  4 * 10-3 6-0 0.3700; *  5 * 10-3 6-0 0.3800; *  6 * 10-3 6-0 0.4300; *  7 * 10-3 6-0 0.5100;"
-               "*  8 * 10-3 6-0 0.6000; *  9 * 10-3 6-0 0.6300; * 10 * 10-3 6-0 0.6300; * 11 * 10-3 6-0 0.6100;"
-               "* 12 * 10-3 6-0 0.6000; * 13 * 10-3 6-0 0.5900; * 14 * 10-3 6-0 0.5900; * 15 * 10-3 6-0 0.6100;"
-               "* 16 * 10-3 6-0 0.7100; * 17 * 10-3 6-0 0.8800; * 18 * 10-3 6-0 0.9600; * 19 * 10-3 6-0 0.9700;"
-               "* 20 * 10-3 6-0 0.9400; * 21 * 10-3 6-0 0.8800; * 22 * 10-3 6-0 0.7600; * 23 * 10-3 6-0 0.5800"
-               "}"
-               },
-               // Plugs (source: ELCAP lit-sp.dat)
-       {       "PLUGS",
-               {30, false, {0.0,0.0,1.0}, 0.90, 0.9},
-               "type:analog; schedule: residential-plugs-default; power: 0.36 kW",
-               "residential-plugs-default",
-               "positive; nonzero; weekday-summer {"
-               "*  0 * 4-9 1-5 0.380; *  1 * 4-9 1-5 0.340; *  2 * 4-9 1-5 0.320; *  3 * 4-9 1-5 0.320;"
-               "*  4 * 4-9 1-5 0.320; *  5 * 4-9 1-5 0.350; *  6 * 4-9 1-5 0.410; *  7 * 4-9 1-5 0.450;"
-               "*  8 * 4-9 1-5 0.450; *  9 * 4-9 1-5 0.450; * 10 * 4-9 1-5 0.450; * 11 * 4-9 1-5 0.450;"
-               "* 12 * 4-9 1-5 0.450; * 13 * 4-9 1-5 0.440; * 14 * 4-9 1-5 0.440; * 15 * 4-9 1-5 0.450;"
-               "* 16 * 4-9 1-5 0.470; * 17 * 4-9 1-5 0.510; * 18 * 4-9 1-5 0.540; * 19 * 4-9 1-5 0.560;"
-               "* 20 * 4-9 1-5 0.630; * 21 * 4-9 1-5 0.710; * 22 * 4-9 1-5 0.650; * 23 * 4-9 1-5 0.490"
-               "}"
-               "weekend-summer {"
-               "*  0 * 4-9 6-0 0.410; *  1 * 4-9 6-0 0.360; *  2 * 4-9 6-0 0.330; *  3 * 4-9 6-0 0.320;"
-               "*  4 * 4-9 6-0 0.320; *  5 * 4-9 6-0 0.320; *  6 * 4-9 6-0 0.340; *  7 * 4-9 6-0 0.390;"
-               "*  8 * 4-9 6-0 0.440; *  9 * 4-9 6-0 0.470; * 10 * 4-9 6-0 0.470; * 11 * 4-9 6-0 0.470;"
-               "* 12 * 4-9 6-0 0.470; * 13 * 4-9 6-0 0.460; * 14 * 4-9 6-0 0.460; * 15 * 4-9 6-0 0.460;"
-               "* 16 * 4-9 6-0 0.470; * 17 * 4-9 6-0 0.490; * 18 * 4-9 6-0 0.520; * 19 * 4-9 6-0 0.540;"
-               "* 20 * 4-9 6-0 0.610; * 21 * 4-9 6-0 0.680; * 22 * 4-9 6-0 0.630; * 23 * 4-9 6-0 0.500"
-               "}"
-               "weekday-winter {"
-               "*  0 * 10-3 1-5 0.4200; *  1 * 10-3 1-5 0.3800; *  2 * 10-3 1-5 0.3700; *  3 * 10-3 1-5 0.3600;"
-               "*  4 * 10-3 1-5 0.3700; *  5 * 10-3 1-5 0.4200; *  6 * 10-3 1-5 0.5800; *  7 * 10-3 1-5 0.6900;"
-               "*  8 * 10-3 1-5 0.6100; *  9 * 10-3 1-5 0.5600; * 10 * 10-3 1-5 0.5300; * 11 * 10-3 1-5 0.5100;"
-               "* 12 * 10-3 1-5 0.4900; * 13 * 10-3 1-5 0.4700; * 14 * 10-3 1-5 0.4700; * 15 * 10-3 1-5 0.5100;"
-               "* 16 * 10-3 1-5 0.6300; * 17 * 10-3 1-5 0.8400; * 18 * 10-3 1-5 0.9700; * 19 * 10-3 1-5 0.9800;"
-               "* 20 * 10-3 1-5 0.9600; * 21 * 10-3 1-5 0.8900; * 22 * 10-3 1-5 0.7400; * 23 * 10-3 1-5 0.5500"
-               "}"
-               "weekend-winter {"
-               "*  0 * 10-3 6-0 0.4900; *  1 * 10-3 6-0 0.4200; *  2 * 10-3 6-0 0.3800; *  3 * 10-3 6-0 0.3800;"
-               "*  4 * 10-3 6-0 0.3700; *  5 * 10-3 6-0 0.3800; *  6 * 10-3 6-0 0.4300; *  7 * 10-3 6-0 0.5100;"
-               "*  8 * 10-3 6-0 0.6000; *  9 * 10-3 6-0 0.6300; * 10 * 10-3 6-0 0.6300; * 11 * 10-3 6-0 0.6100;"
-               "* 12 * 10-3 6-0 0.6000; * 13 * 10-3 6-0 0.5900; * 14 * 10-3 6-0 0.5900; * 15 * 10-3 6-0 0.6100;"
-               "* 16 * 10-3 6-0 0.7100; * 17 * 10-3 6-0 0.8800; * 18 * 10-3 6-0 0.9600; * 19 * 10-3 6-0 0.9700;"
```

```
            "* 20 * 10-3 6-0 0.9400; * 21 * 10-3 6-0 0.8800; * 22 * 10-3 6-0 0.7600; * 23 * 10-3 6-0 0.5800"
            "}"
            },

    {   "CLOTHESWASHER",
            {20, false, {0.0,0.0,1.0}, 0.9, 1.0},
            "type:analog; schedule: residential-clotheswasher-default; power: 1 kW", //energy: 0.75 kWh;
            "residential-clotheswasher-default",
            "positive; nonzero; weekday-summer {"
            "*  0 * 4-9 1-5 0.0029; *  1 * 4-9 1-5 0.0019; *  2 * 4-9 1-5 0.0014; *  3 * 4-9 1-5 0.0013;"
            "*  4 * 4-9 1-5 0.0018; *  5 * 4-9 1-5 0.0026; *  6 * 4-9 1-5 0.0055; *  7 * 4-9 1-5 0.0126;"
            "*  8 * 4-9 1-5 0.0181; *  9 * 4-9 1-5 0.0208; * 10 * 4-9 1-5 0.0229; * 11 * 4-9 1-5 0.0216;"
            "* 12 * 4-9 1-5 0.0193; * 13 * 4-9 1-5 0.0170; * 14 * 4-9 1-5 0.0145; * 15 * 4-9 1-5 0.0135;"
            "* 16 * 4-9 1-5 0.0135; * 17 * 4-9 1-5 0.0142; * 18 * 4-9 1-5 0.0145; * 19 * 4-9 1-5 0.0148;"
            "* 20 * 4-9 1-5 0.0146; * 21 * 4-9 1-5 0.0141; * 22 * 4-9 1-5 0.0110; * 23 * 4-9 1-5 0.0062"
            "}"
            "weekend-summer {"
            "*  0 * 4-9 6-0 0.0031; *  1 * 4-9 6-0 0.0019; *  2 * 4-9 6-0 0.0013; *  3 * 4-9 6-0 0.0012;"
            "*  4 * 4-9 6-0 0.0012; *  5 * 4-9 6-0 0.0016; *  6 * 4-9 6-0 0.0027; *  7 * 4-9 6-0 0.0066;"
            "*  8 * 4-9 6-0 0.0157; *  9 * 4-9 6-0 0.0220; * 10 * 4-9 6-0 0.0258; * 11 * 4-9 6-0 0.0251;"
            "* 12 * 4-9 6-0 0.0231; * 13 * 4-9 6-0 0.0217; * 14 * 4-9 6-0 0.0186; * 15 * 4-9 6-0 0.0157;"
            "* 16 * 4-9 6-0 0.0156; * 17 * 4-9 6-0 0.0151; * 18 * 4-9 6-0 0.0147; * 19 * 4-9 6-0 0.0150;"
            "* 20 * 4-9 6-0 0.0156; * 21 * 4-9 6-0 0.0148; * 22 * 4-9 6-0 0.0106; * 23 * 4-9 6-0 0.0065"
            "}"
            "weekday-winter {"
            "*  0 * 10-3 1-5 0.0036; *  1 * 10-3 1-5 0.0024; *  2 * 10-3 1-5 0.0020; *  3 * 10-3 1-5 0.0019;"
            "*  4 * 10-3 1-5 0.0026; *  5 * 10-3 1-5 0.0040; *  6 * 10-3 1-5 0.0062; *  7 * 10-3 1-5 0.0118;"
            "*  8 * 10-3 1-5 0.0177; *  9 * 10-3 1-5 0.0211; * 10 * 10-3 1-5 0.0215; * 11 * 10-3 1-5 0.0203;"
            "* 12 * 10-3 1-5 0.0176; * 13 * 10-3 1-5 0.0155; * 14 * 10-3 1-5 0.0133; * 15 * 10-3 1-5 0.0130;"
            "* 16 * 10-3 1-5 0.0145; * 17 * 10-3 1-5 0.0159; * 18 * 10-3 1-5 0.0166; * 19 * 10-3 1-5 0.0164;"
            "* 20 * 10-3 1-5 0.0154; * 21 * 10-3 1-5 0.0149; * 22 * 10-3 1-5 0.0110; * 23 * 10-3 1-5 0.0065"
            "}"
            "weekend-winter {"
            "*  0 * 10-3 6-0 0.0044; *  1 * 10-3 6-0 0.0030; *  2 * 10-3 6-0 0.0022; *  3 * 10-3 6-0 0.0020;"
            "*  4 * 10-3 6-0 0.0021; *  5 * 10-3 6-0 0.0021; *  6 * 10-3 6-0 0.0030; *  7 * 10-3 6-0 0.0067;"
            "*  8 * 10-3 6-0 0.0145; *  9 * 10-3 6-0 0.0244; * 10 * 10-3 6-0 0.0310; * 11 * 10-3 6-0 0.0323;"
            "* 12 * 10-3 6-0 0.0308; * 13 * 10-3 6-0 0.0285; * 14 * 10-3 6-0 0.0251; * 15 * 10-3 6-0 0.0224;"
            "* 16 * 10-3 6-0 0.0215; * 17 * 10-3 6-0 0.0203; * 18 * 10-3 6-0 0.0194; * 19 * 10-3 6-0 0.0188;"
            "* 20 * 10-3 6-0 0.0180; * 21 * 10-3 6-0 0.0151; * 22 * 10-3 6-0 0.0122; * 23 * 10-3 6-0 0.0073"
            "}"
            },

    {   "WATERHEATER",
            {30, true, {0.0,0.0,1.0}, 1.0, 0.5},
            "type:analog; schedule: residential-waterheater-default; power: 5 kW", //energy: 1 kWh;
            "residential-waterheater-default",
            "positive; nonzero; weekday-summer {"
            "*  0 * 4-9 1-5 0.21; *  1 * 4-9 1-5 0.16; *  2 * 4-9 1-5 0.13; *  3 * 4-9 1-5 0.12;"
            "*  4 * 4-9 1-5 0.15; *  5 * 4-9 1-5 0.26; *  6 * 4-9 1-5 0.51; *  7 * 4-9 1-5 0.76;"
            "*  8 * 4-9 1-5 0.77; *  9 * 4-9 1-5 0.76; * 10 * 4-9 1-5 0.71; * 11 * 4-9 1-5 0.61;"
            "* 12 * 4-9 1-5 0.54; * 13 * 4-9 1-5 0.49; * 14 * 4-9 1-5 0.43; * 15 * 4-9 1-5 0.41;"
            "* 16 * 4-9 1-5 0.43; * 17 * 4-9 1-5 0.52; * 18 * 4-9 1-5 0.60; * 19 * 4-9 1-5 0.60;"
            "* 20 * 4-9 1-5 0.59; * 21 * 4-9 1-5 0.60; * 22 * 4-9 1-5 0.55; * 23 * 4-9 1-5 0.37"
            "}"
            "weekend-summer {"
            "*  0 * 4-9 6-0 0.23; *  1 * 4-9 6-0 0.17; *  2 * 4-9 6-0 0.14; *  3 * 4-9 6-0 0.13;"
            "*  4 * 4-9 6-0 0.13; *  5 * 4-9 6-0 0.17; *  6 * 4-9 6-0 0.26; *  7 * 4-9 6-0 0.45;"
            "*  8 * 4-9 6-0 0.69; *  9 * 4-9 6-0 0.85; * 10 * 4-9 6-0 0.84; * 11 * 4-9 6-0 0.76;"
            "* 12 * 4-9 6-0 0.65; * 13 * 4-9 6-0 0.58; * 14 * 4-9 6-0 0.49; * 15 * 4-9 6-0 0.46;"
            "* 16 * 4-9 6-0 0.46; * 17 * 4-9 6-0 0.50; * 18 * 4-9 6-0 0.54; * 19 * 4-9 6-0 0.55;"
            "* 20 * 4-9 6-0 0.56; * 21 * 4-9 6-0 0.56; * 22 * 4-9 6-0 0.49; * 23 * 4-9 6-0 0.38"
            "}"
            "weekday-winter {"
            "*  0 * 10-3 1-5 0.25; *  1 * 10-3 1-5 0.19; *  2 * 10-3 1-5 0.16; *  3 * 10-3 1-5 0.15;"
            "*  4 * 10-3 1-5 0.18; *  5 * 10-3 1-5 0.34; *  6 * 10-3 1-5 0.74; *  7 * 10-3 1-5 1.20;"
            "*  8 * 10-3 1-5 1.10; *  9 * 10-3 1-5 0.94; * 10 * 10-3 1-5 0.82; * 11 * 10-3 1-5 0.71;"
            "* 12 * 10-3 1-5 0.62; * 13 * 10-3 1-5 0.55; * 14 * 10-3 1-5 0.48; * 15 * 10-3 1-5 0.47;"
            "* 16 * 10-3 1-5 0.54; * 17 * 10-3 1-5 0.68; * 18 * 10-3 1-5 0.83; * 19 * 10-3 1-5 0.82;"
            "* 20 * 10-3 1-5 0.74; * 21 * 10-3 1-5 0.68; * 22 * 10-3 1-5 0.57; * 23 * 10-3 1-5 0.40"
            "}"
            "weekend-winter {"
            "*  0 * 10-3 6-0 0.29; *  1 * 10-3 6-0 0.22; *  2 * 10-3 6-0 0.17; *  3 * 10-3 6-0 0.15;"
            "*  4 * 10-3 6-0 0.16; *  5 * 10-3 6-0 0.19; *  6 * 10-3 6-0 0.27; *  7 * 10-3 6-0 0.47;"
            "*  8 * 10-3 6-0 0.82; *  9 * 10-3 6-0 1.08; * 10 * 10-3 6-0 1.15; * 11 * 10-3 6-0 1.08;"
            "* 12 * 10-3 6-0 0.98; * 13 * 10-3 6-0 0.87; * 14 * 10-3 6-0 0.77; * 15 * 10-3 6-0 0.69;"
            "* 16 * 10-3 6-0 0.72; * 17 * 10-3 6-0 0.78; * 18 * 10-3 6-0 0.83; * 19 * 10-3 6-0 0.79;"
            "* 20 * 10-3 6-0 0.72; * 21 * 10-3 6-0 0.64; * 22 * 10-3 6-0 0.53; * 23 * 10-3 6-0 0.43"
            "}"
            },

    {   "REFRIGERATOR",
            {20, false, {0.1,0.0,0.9}, 0.9, 1.0},
            "type:analog; schedule: residential-refrigerator-default; power: 750 W", //energy: 1 kWh;
            "residential-refrigerator-default",
            "positive; nonzero; weekday-summer {"
            "*  0 * 4-9 1-5 0.187; *  1 * 4-9 1-5 0.182; *  2 * 4-9 1-5 0.176; *  3 * 4-9 1-5 0.170;"
            "*  4 * 4-9 1-5 0.168; *  5 * 4-9 1-5 0.168; *  6 * 4-9 1-5 0.177; *  7 * 4-9 1-5 0.174;"
            "*  8 * 4-9 1-5 0.177; *  9 * 4-9 1-5 0.180; * 10 * 4-9 1-5 0.180; * 11 * 4-9 1-5 0.183;"
            "* 12 * 4-9 1-5 0.192; * 13 * 4-9 1-5 0.192; * 14 * 4-9 1-5 0.194; * 15 * 4-9 1-5 0.196;"
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–                   "* 16 * 4-9 1-5 0.205; * 17 * 4-9 1-5 0.217; * 18 * 4-9 1-5 0.225; * 19 * 4-9 1-5 0.221;"
–                   "* 20 * 4-9 1-5 0.216; * 21 * 4-9 1-5 0.214; * 22 * 4-9 1-5 0.207; * 23 * 4-9 1-5 0.195"
–                   "}"
–                   "weekend-summer {"
–                   "*  0 * 4-9 6-0 0.187; *  1 * 4-9 6-0 0.181; *  2 * 4-9 6-0 0.176; *  3 * 4-9 6-0 0.169;"
–                   "*  4 * 4-9 6-0 0.166; *  5 * 4-9 6-0 0.164; *  6 * 4-9 6-0 0.167; *  7 * 4-9 6-0 0.169;"
–                   "*  8 * 4-9 6-0 0.180; *  9 * 4-9 6-0 0.184; * 10 * 4-9 6-0 0.187; * 11 * 4-9 6-0 0.187;"
–                   "* 12 * 4-9 6-0 0.195; * 13 * 4-9 6-0 0.200; * 14 * 4-9 6-0 0.201; * 15 * 4-9 6-0 0.203;"
–                   "* 16 * 4-9 6-0 0.209; * 17 * 4-9 6-0 0.218; * 18 * 4-9 6-0 0.222; * 19 * 4-9 6-0 0.221;"
–                   "* 20 * 4-9 6-0 0.217; * 21 * 4-9 6-0 0.216; * 22 * 4-9 6-0 0.207; * 23 * 4-9 6-0 0.196"
–                   "}"
–                   "weekday-winter {"
–                   "*  0 * 10-3 1-5 0.1530; *  1 * 10-3 1-5 0.1500; *  2 * 10-3 1-5 0.1460; *  3 * 10-3 1-5 0.1420;"
–                   "*  4 * 10-3 1-5 0.1400; *  5 * 10-3 1-5 0.1450; *  6 * 10-3 1-5 0.1520; *  7 * 10-3 1-5 0.1600;"
–                   "*  8 * 10-3 1-5 0.1580; *  9 * 10-3 1-5 0.1580; * 10 * 10-3 1-5 0.1560; * 11 * 10-3 1-5 0.1560;"
–                   "* 12 * 10-3 1-5 0.1630; * 13 * 10-3 1-5 0.1620; * 14 * 10-3 1-5 0.1590; * 15 * 10-3 1-5 0.1620;"
–                   "* 16 * 10-3 1-5 0.1690; * 17 * 10-3 1-5 0.1850; * 18 * 10-3 1-5 0.1920; * 19 * 10-3 1-5 0.1820;"
–                   "* 20 * 10-3 1-5 0.1800; * 21 * 10-3 1-5 0.1760; * 22 * 10-3 1-5 0.1670; * 23 * 10-3 1-5 0.1590"
–                   "}"
–                   "weekend-winter {"
–                   "*  0 * 10-3 6-0 0.1560; *  1 * 10-3 6-0 0.1520; *  2 * 10-3 6-0 0.1470; *  3 * 10-3 6-0 0.1430;"
–                   "*  4 * 10-3 6-0 0.1420; *  5 * 10-3 6-0 0.1430; *  6 * 10-3 6-0 0.1430; *  7 * 10-3 6-0 0.1500;"
–                   "*  8 * 10-3 6-0 0.1610; *  9 * 10-3 6-0 0.1690; * 10 * 10-3 6-0 0.1670; * 11 * 10-3 6-0 0.1660;"
–                   "* 12 * 10-3 6-0 0.1740; * 13 * 10-3 6-0 0.1760; * 14 * 10-3 6-0 0.1740; * 15 * 10-3 6-0 0.1750;"
–                   "* 16 * 10-3 6-0 0.1790; * 17 * 10-3 6-0 0.1910; * 18 * 10-3 6-0 0.1930; * 19 * 10-3 6-0 0.1870;"
–                   "* 20 * 10-3 6-0 0.1840; * 21 * 10-3 6-0 0.1780; * 22 * 10-3 6-0 0.1700; * 23 * 10-3 6-0 0.1600"
–                   "}"
–                   },
–
–           {   "DRYER",
–                   {30, true, {0.9,0.0,0.1}, 0.99, 0.15},
–                   "type:analog; schedule: residential-dryer-default; power: 5 kW", //energy: 2.5 kWh;
–                   "residential-dryer-default",
–                   "positive; nonzero; weekday-summer {"
–                   "*  0 * 4-9 1-5 0.036; *  1 * 4-9 1-5 0.013; *  2 * 4-9 1-5 0.007; *  3 * 4-9 1-5 0.005;"
–                   "*  4 * 4-9 1-5 0.005; *  5 * 4-9 1-5 0.017; *  6 * 4-9 1-5 0.048; *  7 * 4-9 1-5 0.085;"
–                   "*  8 * 4-9 1-5 0.115; *  9 * 4-9 1-5 0.156; * 10 * 4-9 1-5 0.179; * 11 * 4-9 1-5 0.185;"
–                   "* 12 * 4-9 1-5 0.172; * 13 * 4-9 1-5 0.162; * 14 * 4-9 1-5 0.145; * 15 * 4-9 1-5 0.136;"
–                   "* 16 * 4-9 1-5 0.133; * 17 * 4-9 1-5 0.134; * 18 * 4-9 1-5 0.127; * 19 * 4-9 1-5 0.130;"
–                   "* 20 * 4-9 1-5 0.141; * 21 * 4-9 1-5 0.154; * 22 * 4-9 1-5 0.138; * 23 * 4-9 1-5 0.083"
–                   "}"
–                   "weekend-summer {"
–                   "*  0 * 4-9 6-0 0.041; *  1 * 4-9 6-0 0.017; *  2 * 4-9 6-0 0.008; *  3 * 4-9 6-0 0.005;"
–                   "*  4 * 4-9 6-0 0.005; *  5 * 4-9 6-0 0.007; *  6 * 4-9 6-0 0.018; *  7 * 4-9 6-0 0.047;"
–                   "*  8 * 4-9 6-0 0.100; *  9 * 4-9 6-0 0.168; * 10 * 4-9 6-0 0.205; * 11 * 4-9 6-0 0.220;"
–                   "* 12 * 4-9 6-0 0.211; * 13 * 4-9 6-0 0.210; * 14 * 4-9 6-0 0.188; * 15 * 4-9 6-0 0.168;"
–                   "* 16 * 4-9 6-0 0.154; * 17 * 4-9 6-0 0.146; * 18 * 4-9 6-0 0.138; * 19 * 4-9 6-0 0.137;"
–                   "* 20 * 4-9 6-0 0.144; * 21 * 4-9 6-0 0.155; * 22 * 4-9 6-0 0.131; * 23 * 4-9 6-0 0.081"
–                   "}"
–                   "weekday-winter {"
–                   "*  0 * 10-3 1-5 0.0360; *  1 * 10-3 1-5 0.0160; *  2 * 10-3 1-5 0.0100; *  3 * 10-3 1-5 0.0070;"
–                   "*  4 * 10-3 1-5 0.0090; *  5 * 10-3 1-5 0.0230; *  6 * 10-3 1-5 0.0610; *  7 * 10-3 1-5 0.1030;"
–                   "*  8 * 10-3 1-5 0.1320; *  9 * 10-3 1-5 0.1750; * 10 * 10-3 1-5 0.2050; * 11 * 10-3 1-5 0.2130;"
–                   "* 12 * 10-3 1-5 0.1940; * 13 * 10-3 1-5 0.1770; * 14 * 10-3 1-5 0.1610; * 15 * 10-3 1-5 0.1560;"
–                   "* 16 * 10-3 1-5 0.1640; * 17 * 10-3 1-5 0.1710; * 18 * 10-3 1-5 0.1610; * 19 * 10-3 1-5 0.1590;"
–                   "* 20 * 10-3 1-5 0.1670; * 21 * 10-3 1-5 0.1690; * 22 * 10-3 1-5 0.1380; * 23 * 10-3 1-5 0.0820"
–                   "}"
–                   "weekend-winter {"
–                   "*  0 * 10-3 6-0 0.0390; *  1 * 10-3 6-0 0.0190; *  2 * 10-3 6-0 0.0110; *  3 * 10-3 6-0 0.0070;"
–                   "*  4 * 10-3 6-0 0.0080; *  5 * 10-3 6-0 0.0090; *  6 * 10-3 6-0 0.0160; *  7 * 10-3 6-0 0.0430;"
–                   "*  8 * 10-3 6-0 0.1010; *  9 * 10-3 6-0 0.1810; * 10 * 10-3 6-0 0.2640; * 11 * 10-3 6-0 0.3050;"
–                   "* 12 * 10-3 6-0 0.3110; * 13 * 10-3 6-0 0.3060; * 14 * 10-3 6-0 0.2850; * 15 * 10-3 6-0 0.2700;"
–                   "* 16 * 10-3 6-0 0.2600; * 17 * 10-3 6-0 0.2450; * 18 * 10-3 6-0 0.2200; * 19 * 10-3 6-0 0.1980;"
–                   "* 20 * 10-3 6-0 0.1880; * 21 * 10-3 6-0 0.1790; * 22 * 10-3 6-0 0.1480; * 23 * 10-3 6-0 0.0930"
–                   "}"
–                   },
–
–           {   "FREEZER",
–                   {20, false, {0.1,0.0,0.9}, 0.9, 1.0},
–                   "type:analog; schedule: residential-freezer-default; power: 500 W", //energy: 750 Wh;
–                   "residential-freezer-default",
–                   "positive; nonzero; weekday-summer {"
–                   "*  0 * 4-9 1-5 0.210; *  1 * 4-9 1-5 0.213; *  2 * 4-9 1-5 0.208; *  3 * 4-9 1-5 0.202;"
–                   "*  4 * 4-9 1-5 0.203; *  5 * 4-9 1-5 0.198; *  6 * 4-9 1-5 0.190; *  7 * 4-9 1-5 0.186;"
–                   "*  8 * 4-9 1-5 0.189; *  9 * 4-9 1-5 0.194; * 10 * 4-9 1-5 0.199; * 11 * 4-9 1-5 0.202;"
–                   "* 12 * 4-9 1-5 0.211; * 13 * 4-9 1-5 0.214; * 14 * 4-9 1-5 0.219; * 15 * 4-9 1-5 0.222;"
–                   "* 16 * 4-9 1-5 0.230; * 17 * 4-9 1-5 0.228; * 18 * 4-9 1-5 0.229; * 19 * 4-9 1-5 0.223;"
–                   "* 20 * 4-9 1-5 0.224; * 21 * 4-9 1-5 0.223; * 22 * 4-9 1-5 0.218; * 23 * 4-9 1-5 0.214"
–                   "}"
–                   "weekend-summer {"
–                   "*  0 * 4-9 6-0 0.203; *  1 * 4-9 6-0 0.202; *  2 * 4-9 6-0 0.202; *  3 * 4-9 6-0 0.193;"
–                   "*  4 * 4-9 6-0 0.198; *  5 * 4-9 6-0 0.195; *  6 * 4-9 6-0 0.191; *  7 * 4-9 6-0 0.183;"
–                   "*  8 * 4-9 6-0 0.184; *  9 * 4-9 6-0 0.192; * 10 * 4-9 6-0 0.197; * 11 * 4-9 6-0 0.202;"
–                   "* 12 * 4-9 6-0 0.208; * 13 * 4-9 6-0 0.219; * 14 * 4-9 6-0 0.219; * 15 * 4-9 6-0 0.225;"
–                   "* 16 * 4-9 6-0 0.225; * 17 * 4-9 6-0 0.225; * 18 * 4-9 6-0 0.223; * 19 * 4-9 6-0 0.219;"
–                   "* 20 * 4-9 6-0 0.221; * 21 * 4-9 6-0 0.220; * 22 * 4-9 6-0 0.215; * 23 * 4-9 6-0 0.209"
–                   "}"
–                   "weekday-winter {"
–                   "*  0 * 10-3 1-5 0.149; *  1 * 10-3 1-5 0.148; *  2 * 10-3 1-5 0.145; *  3 * 10-3 1-5 0.144;"
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```
                "*  4 * 10-3 1-5 0.143; *  5 * 10-3 1-5 0.140; *  6 * 10-3 1-5 0.138; *  7 * 10-3 1-5 0.138;"
                "*  8 * 10-3 1-5 0.140; *  9 * 10-3 1-5 0.141; * 10 * 10-3 1-5 0.142; * 11 * 10-3 1-5 0.147;"
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                "* 16 * 4-9 1-5 0.0124; * 17 * 4-9 1-5 0.0156; * 18 * 4-9 1-5 0.0278; * 19 * 4-9 1-5 0.0343;"
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                "* 16 * 4-9 1-5 0.094; * 17 * 4-9 1-5 0.168; * 18 * 4-9 1-5 0.148; * 19 * 4-9 1-5 0.086;"
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                "* 16 * 4-9 6-0 0.091; * 17 * 4-9 6-0 0.134; * 18 * 4-9 6-0 0.121; * 19 * 4-9 6-0 0.080;"
                "* 20 * 4-9 6-0 0.052; * 21 * 4-9 6-0 0.035; * 22 * 4-9 6-0 0.022; * 23 * 4-9 6-0 0.011"
                "}"
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-               "*  8 * 4-9 1-5 0.044; *  9 * 4-9 1-5 0.042; * 10 * 4-9 1-5 0.042; * 11 * 4-9 1-5 0.053;"
-               "* 12 * 4-9 1-5 0.057; * 13 * 4-9 1-5 0.046; * 14 * 4-9 1-5 0.044; * 15 * 4-9 1-5 0.053;"
-               "* 16 * 4-9 1-5 0.094; * 17 * 4-9 1-5 0.168; * 18 * 4-9 1-5 0.148; * 19 * 4-9 1-5 0.086;"
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-               "*  8 * 4-9 6-0 0.060; *  9 * 4-9 6-0 0.068; * 10 * 4-9 6-0 0.065; * 11 * 4-9 6-0 0.067;"
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-               "* 16 * 4-9 6-0 0.091; * 17 * 4-9 6-0 0.134; * 18 * 4-9 6-0 0.121; * 19 * 4-9 6-0 0.080;"
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-               "*  4 * 10-3 1-5 0.009; *  5 * 10-3 1-5 0.016; *  6 * 10-3 1-5 0.032; *  7 * 10-3 1-5 0.050;"
-               "*  8 * 10-3 1-5 0.045; *  9 * 10-3 1-5 0.043; * 10 * 10-3 1-5 0.045; * 11 * 10-3 1-5 0.059;"
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-               "*  4 * 10-3 6-0 0.010; *  5 * 10-3 6-0 0.012; *  6 * 10-3 6-0 0.018; *  7 * 10-3 6-0 0.040;"
-               "*  8 * 10-3 6-0 0.073; *  9 * 10-3 6-0 0.094; * 10 * 10-3 6-0 0.091; * 11 * 10-3 6-0 0.100;"
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-               "* 20 * 10-3 6-0 0.050; * 21 * 10-3 6-0 0.033; * 22 * 10-3 6-0 0.022; * 23 * 10-3 6-0 0.014"
-               "}"
-       },
-
-       /// @todo add other implicit enduse schedules and shapes as they are defined
+#include "bsra2014.h"
 };

 EXPORT CIRCUIT *attach_enduse_house_e(OBJECT *obj, enduse *target, double breaker_amps, int is220)
```

Appendix C

Glossary

Area control error
The instantaneous difference between the actual and scheduled interchange, taking into account the effects of frequency bias.

Baseload
The minimum load for a given control area. This load is constant.

Baseload generating capacity
The fleet of generators that operate continuously around the clock, as opposed to midload and peakload generators (see *peaker*).

Bulk (power) system
See *grid*.

Clearing price/quantity
The price (and quantity) that results in a market with supply equal to demand.

Congestion
A congested line is one that would be overloaded were a limit not enforced. In a market, the path from A to B is congested if the price at B is greater than the price at A.

Contingency
The unexpected failure or outage of a system component, such as a generator, transmission asset, or load. A single contingency may involve multiple assets.

Control area
The bounded region of an electricity interconnection through which interchange is observed and within which generation is controlled to manage the scheduled flow of power.

Demand
The amount of power that would be consumed by loads if the system were operating at normal frequency and voltage for all consumers, including losses.

Demand elasticity

The responsiveness of the quantity demanded of a good to its own price. Short for price elasticity of demand. Defined as the fractional change in demand in response to a fractional change in price, or $(P/Q)(dQ/dP)$.

Dispatch

The operation and control a power system by determining the outputs of generators necessary to satisfy demand.

Double auction

A market where both buyers and sellers of a commodity meet at one place or communicate with a central auctioneer to buy or sell an asset.

Economic dispatch

Dispatch that satisfies a minimum production cost objective given transmission constraints.

Equilibrium demand/load

The demand/load in the absence of any changing conditions after a quasi-infinite time.

Frequency

The rate at which alternating current complete a cycle of two reversals of direction. There is a single frequency for an entire interconnection and control areas cannot have different individual frequencies.

Grid

An electricity transmission network.

Interconnection

One of the five major bulk power systems in North America: Eastern, Western, Texas, Quebec, and Alaska. An interconnection is the largest synchronized portion of any power system and must have a single frequency. Thus only DC lines can connect interconnections.

Independent system operator

A non-profit entity that runs the real-time balancing market and often also the day-ahead energy markets.

Locational Marginal Price

The different derivatives of price with respect to a change in quantity for nodes in an interconnection that arise from congestion in the system.

Load

An end-use device or customer that consumes power from the electric system. Sometimes used interchangeably with *demand* but it is in fact subtly different.

Demand is what the load would have been were there no constraints or incentives for it to change. Sometimes demand refers to the entire ranges of possible loads, while load refers to realized value given system conditions.

Marginal Forgone Retail Rate
The consumer's opportunity cost for not consuming the last increment of demand.

Marginal production cost
The derivative of the total cost with respect to output. Includes fixed, variable, startup, no-load and shutdown costs.

Fixed cost: Includes debt and equity costs that do not depend on output.

Variable cost: Includes costs that vary as a function of output.

Startup/shutdown cost: Includes costs that are incurred as a result of starting and stopping.

No-load cost: Includes costs of running a plant at zero-output.

Market
Any situation in which the sale and purchase of goods or services takes place.

Market power
The ability of a market participant to profitably alter prices away from the competitive equilibrium, i.e., the conditions where (a) there are one or more price-taking producers to supply a given quantity and (b) there are one or more price-taking consumers to demand the same quantity.

Monopoly
The condition where a single market participant can act as the sole supplier of a good or service for which there are no substitutes and many buyers.

Monopsony
The condition where a single market participant can act as the sole consumer of a good or service for which there are no substitutes and many sellers.

Reserve (resources)
Generating resources available on short notice in excess of demand.

Regulation reserves: Generation that is used constantly to balance fluctuations in load and intermittent generation.

Spinning reserves: Generation that is available online that can respond to a contingency.

Non-spinning reserves: Generation that is available offline to replace spinning reservces in the event of a contingency.

Planning reserve: The difference between the peak load and the peak capacity.

Outage

The forced or planned removal of a generation unit, transmission line or load from service.

Peaker

A peak-load plant that follows diurnal load fluctuations on the most heavily loaded days of the year. Peakers usually have higher variable costs and lower fixed costs.

Power

The rate of flow of energy, specified as real or reactive power.

Real power The power delivered to the load that can be converted to actual work.

Reactive power The power necessary to deliver real power to the load while maintaining the AC voltage and current relationship in the transmission system.

Losses The power lost as heat in the transmission system between the generation and load.

Price

The price of electric energy (measured in $\$/MWh$ or $¢/kWh$).

Profit

The income from the sale of a good or service less the production costs.

Quantity

The amount of electric energy (measured in MWh or kWh).

Ramping

The increasing or decreasing output capability of a generator.

Reliability

The ability of power system to deliver power within the normal voltage and frequency constraints. A power system is reliable if it satisfies both adequacy and security limits.

Adequacy: The ability of the power system to supply the load at all times, taking into account scheduled and reasonable unscheduled outages.

Security: The ability of the power system to withstand disturbances such as electrical faults and sudden loss of assets and services.

Strike Price

The price at which a market participant exercises an option to buy or sell a good or service.

Surplus

The difference between the product's value to the consumer and its cost of production. Also the sum of the consumer and producer surpluses.

Consumer surplus The benefit to the consumer who consumes the good relative to the benefit to the same consumer when he does not consume the good.

Producer surplus The profit to the producer who produces the good relative to the profit to the same producer when he does not produce the good.

Tariff

The body of rules governing the prices at which energy is bought and sold in a market.

Unit commitment

The starting of a generator. Solving the optimal unit commitment is a complex mathematical problem.

Withholding

Reducing output below the competitive price-taking level at the market clearing price. It can be financial by increasing the asking price, or physical by decreasing the offer quantity.

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