UTILIZING BUILDING'S INTRINSIC EQUIPMENT FOR ENERGY STORAGE USING DEMAND RESPONSE

by

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LIST OF ABBREVIATIONS

EIA U.S Energy and Information Administration

PV Photovoltaic

EP Energy Plus

DOE U.S Department of Energy

IDF Intermediate Data Format

HVAC Heating Ventilation and Air Conditioning

PHS Pump Hydro Storage

EV Electric Vehicle

WH Water Heater

TMY3 Typical Meteorological Year, version 3

PNNL Pacific Northwest National Laboratory

GMT Greenwich Mean Time

COP Coefficient Of Performance

EMM Energy Market Module

NEMS National Energy Modelling System

CD Census Division

CR Census Region

CSV Comma Separated Value

CPLE Duke Energy Progress East

AMI Advanced Metering Infrastructure

EFS Electrification Future Study

NREL National Renewable Energy Laboratory

VRE Variable Renewable Energy

EPRI Electric Power Research Institute

ESS Energy Storage System

DHW Daily Hot Water

ABSTRACT

SUMIT KUMAR SRIVASTAVA. UTILIZING BUILDING'S INTRINSIC EQUIPMENT FOR ENERGY STORAGE USING DEMAND RESPONSE. (Under the direction of DR. ROBERT COX)

The increased use of renewables (solar, wind, etc.) as an alternative to the conventional generation using fossil fuels is the solution [1] to address the carbon emission's problem. However, due to the excess penetration of solar Photovoltaic (PV) (centralized or distributed) along conventional generation arises, an imbalance in supply and demand of electricity which leads to an over-voltage challenge for the distribution side of the grid. This over-voltage may be mitigated by curtailing solar PV, which does not solve the underlying issue of carbon emission into the environment. The way out to deploy more PV during daytime is to have a storage that can store the excess generation. As per DOE, the Pump Hydro Storage (PHS) account for 95.41% of total energy storage in the US while other 4.59% is in form of battery and thermal storage. There are many problems associated with PHS such that it needs large and specific geographical area for upper and lower reservoir, detailed planning, and construction time with large capital investment. Batteries come with their own environmental issues as they use raw materials such as lithium and lead and can be hazardous to the environment if they are not disposed and recycled properly. Hence, this study aims to give a feasible solution to utilize the copious number of renewables to generate power with the specific goal of enabling higher penetration of PV on the grid during the day. For the study, various naturally occurring consumer loads have been identified, such as water heaters, Heating Ventilation and Air Conditionings (HVACs), and water/ice thermal storage that can enable high levels of solar PV penetration. The study also presents the energy added onto the grid using simulations for a chosen day and cost comparison between the thermal storage capacity and battery storage.

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CHAPTER 1: INTRODUCTION AND BACKGROUND

1.1 Motivation

Fossil fuels provided about 60.2% of electricity in the United States in 2022, accounting for approximately 31% of overall CO_2 emissions [8]. Corporations and governments are attempting to reduce these emissions and their harmful effects by introducing more renewable resources. Generation from renewable resources such as wind and solar PV has thus been growing steadily in recent years. Although only representing about 3.4% of utility-scale electricity in 2022 [9], solar PV has reached staggering levels in some areas. In fact, it represented about 17.4% of total electricity production in California in 2021 [10]. Fig. 1.1 shows that annual solar deployments in the US are projected to more than double by 2033, reaching over 70 $\mathrm{GW_{DC}}$ annually.

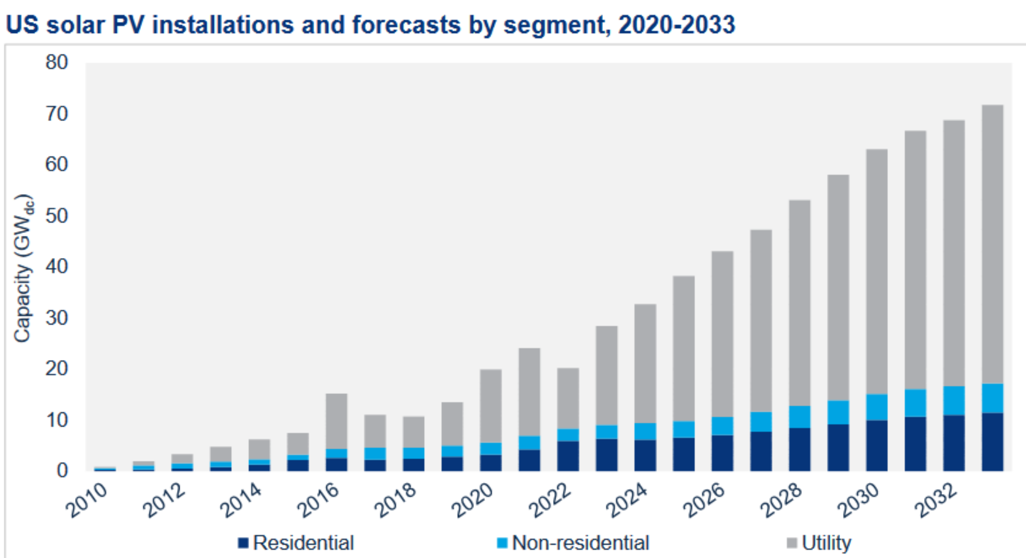


Figure 1.1: Wood Mackenzie: US solar PV installations and forecasts by segment, 2020-2023. Adapted from [2].

Increased solar generation comes with its own set of challenges. Most importantly, solar energy is not dispatchable, meaning that it cannot be controlled by grid operators [11]. In a state like California, for example, which has high-levels of PV penetration, there can be more solar energy entering the grid during sunny conditions than there is load. A new term was introduced to describe this phenomenon known as the **"Duck Curve"** [12].

1.1.1 The Duck Curve

Figure 1.2 describes this concept. The blue-green trend line shows the gross system load on the California Independent System Operator (CAISO) grid at five minute intervals throughout April 16, 2023. The purple trend, on the other hand, shows the net load [3], which is the gross load minus the uncontrollable wind and solar resource generation levels. This behavior creates tremendous challenges for grid operation. For example, Fig. 1.2 shows a time when the net load actually reaches to zero for several minutes, meaning that no conventional generation is needed. As the day passes and the net load varies, conventional generators must prepare to respond rapidly to these fluctuations.

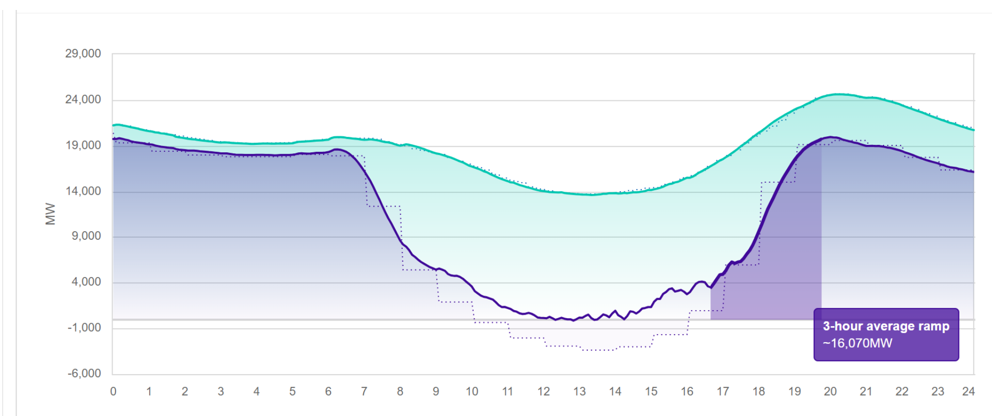


Figure 1.2: Cal ISO duck curve, [3]

The phenomenon shown in Fig. 1.2 presents two challenges related to increasing solar energy adoption. The first challenge is grid stress. The extreme swing in demand for electricity from conventional power plants from midday to late evenings, when energy demand is still high but solar generation has dropped off, means that conventional power plants (such as natural gas-fired plants) must quickly ramp up electricity production to meet consumer demand. That rapid ramp up makes it more difficult for grid operators to match grid supply (the power they are generating) with grid demand in real time. In addition, if more solar power is produced than the grid can use, operators might have to curtail solar power to prevent overgeneration. The other challenge is economic. The dynamics of the duck curve can challenge the traditional economics of dispatchable power plants because the factors contributing to the curve reduce the amount of time a conventional power plant operates, which results in reduced energy revenues. If the reduced revenues make the plants uneconomical to maintain, the plants may retire without a dispatchable replacement. Less dispatchable electricity makes it harder for grid managers to balance electricity supply and demand in a system with wide swings in net demand [13].

The challenges posed by high levels of intermittent renewable energy continue to grow. Fig. 1.3 shows how much change has occurred between 2018 and 2023. The net load now changes so rapidly, that the EPRI coined the term **"canyon curve."** [4]

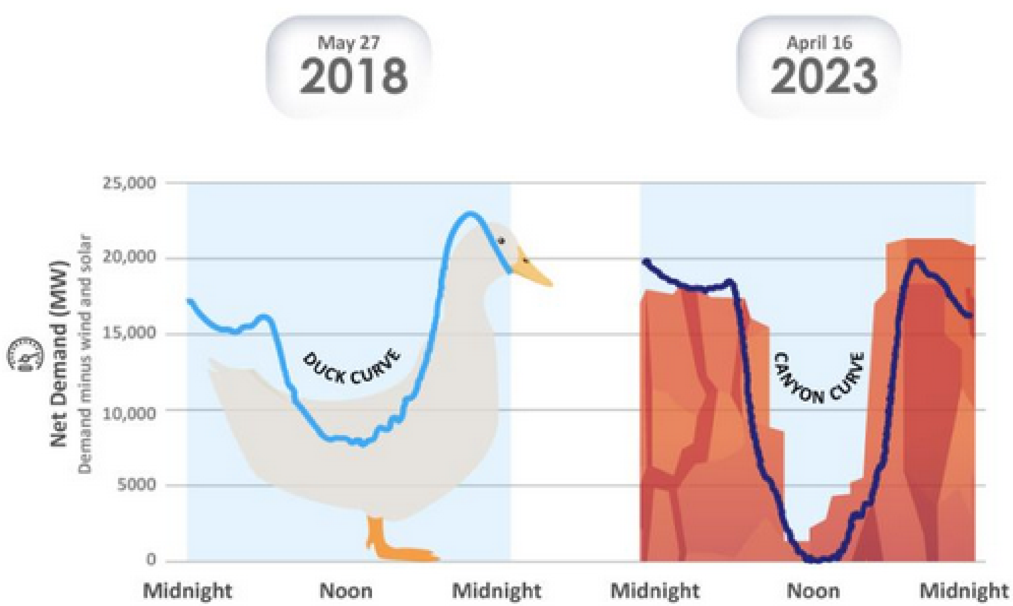


Figure 1.3: Duck and Canyon Curve introduced by EPRI. Adapted from [4]

Solutions have been proposed to address the phenomenon described in Fig. 1.2. Reference [12], for example describes the following ten strategies:

1. Target energy efficiency to the hours when load ramps up sharply.
2. Acquire and deploy peak-oriented renewable resources.
3. Manage water and wastewater pumping loads.
4. Control electric water heaters to reduce peak demand and increase load at strategic hours.
5. Convert commercial air conditioning to ice storage or chilled-water storage.
6. Focus utility prices on the "ramping" hours to enable price-induced changes in load.
7. Deploy electrical energy storage in targeted locations.
8. Implement aggressive demand-response programs.
9. Use inter-regional power exchanges to take advantages of diversity in loads and resources.
10. Retire inflexible plants with high off-peak must-run requirements.

1.1.1.1 Electrification Futures Study from NREL

It is ideated that the future power grid will have more renewable and electricity fueled components in the energy mix as there is a big push for decarbonization in the power sector to mitigate the effect of climate change as much as possible [14], [15]. This electrification shifting energy consumption away from non-electric sources to final point of consumption could lead to profound changes in electricity demand in several ways [16]:

1. Fuel switching from direct combustion of fossil and/or biomass fuels to electricity, could increase the total amount of annual electricity consumption.

2. Electrification could change the electricity demand profiles.

3. Electrification has the potential to dramatically lower primary energy demand due to the higher efficiency of end-use devices especially if power is supplied by renewable energy.

Parallel to demand supply side, electrification is also transforming the generation mix. The penetration of solar and wind generation is expected to increase which influences the power system in all the aspect be it system planning or operations. The deployment of natural-gas along with storage can offer greater flexibility for the system to respond to demand change, Variable Renewable Energy (VRE) energy generation, or outages and other unexpected imbalances.

The NREL report [16], found from its analysis that the operation of the power system under high levels of electrified demand is feasible at the hourly level - even with unprecedented amounts (total installed capacity of 1.3 TW) of VRE for the US - and the operational efficiency of such systems can be enhanced through the expansion of demand-side flexibility, especially flexibility from newly electrified loads.

The other findings are as follows:

- The US power system can operate under scenarios with widespread electrification and associated changes to electricity demand patterns with high levels of VRE penetration (66% of annual national generation) through the expansion and investment in existing commercial technologies.

- Demand-side flexibility mainly from optimized vehicle charging but also from flexible operations of other end-use equipment used in buildings and industry can result in observable changes in how the power system operates, such as reduced system net load ramps and reduced thermal plant cycling. And it can alleviate the challenges of operating a high VRE power system under high electrification by providing energy shifting and operation reserves, resulting in improved operational reliability and lowered VRE curtailment (upto 60 TWh or 16% less curtailment in high electrification scenario with high renewable and high flexible load compared to high electrification scenario with high renewable and no flexible load).

- Assuming no or low operating costs with demand side flexibility, flexible loads in highly electrified futures can lower power system operation costs by providing high value grid services during periods of system stress and by increasing the utilization of more efficient lower cost units. This results in gross operational values of \$9/MWh to \$16/MWh of available flexible load capacity and \$17/MWh to \$22/MWh of shifted load.

- Coupling demand-side flexibility with VRE enhances the ability of electrification to decarbonize the energy sector, because demand-side flexibility is effective in boosting generation from the least-cost sources. High electrification scenario with high renewable and high flexible load can result in 8.3% carbon emission reduction (44.4 million tonnes of CO_2) compared to high electrification scenario with high renewable and no flexible load.

1.1.2 Background on Energy Storage

Energy storage is a unique grid asset capable of providing a variety of applications. As the electric power grid evolves toward a smarter and more reliable grid, with increased amounts of variable renewable generation, the need for energy storage will only increase. On the grid side, energy storage systems (ESSs) can participate in electricity markets by providing services such as energy arbitrage, frequency regulation, and spinning reserves. On the customer side, ESSs can provide a wide range of applications from on-site back-up power, storage for renewable systems to solutions for load shifting, and peak shaving for commercial/industrial businesses [17].

Energy storage applications are often classified based on their duration. The short-duration applications, often referred to as power applications, involve the injection of real or reactive power over short time scales (e.g., seconds to minutes) to maintain the stability of the power grid. For example, frequency regulation is the second-by-second adjustment of output power to maintain the nominal grid frequency. Other examples include voltage support, small signal stability, virtual inertia, and renewable capacity firming. On the other hand, long-duration applications, often called energy applications, typically involve long discharge/charge cycles lasting more than several hours. In many cases, these applications require a high energy capacity (MWh) rating of the storage device to enable the long discharge times at maximum power. The report [18] discerns the storage opportunity drivers:

- Modular storage technology development in response to the growing market for hybrid vehicles and for portable electronic devices.
- Increasing interest in managing peak demand and reliance on "demand response" programs due to peaking generation and transmission constraints.
- Expected increased penetration of distributed energy resources.
- Adoption of the Renewables Portfolio Standard, which will drive increased use of renewables generation with intermittent output.
- Financial risk that limits investment in new transmission capacity, coupled with increasing congestion on some transmission lines and the need for new transmission capacity in many regions.
- Increasing emphasis on richer electric energy and services pricing, such as time-of-use energy prices, locational marginal pricing, and increasing exposure of

market-based prices for ancillary services.

- The increasing use of distributed energy resources and the emergence of Smart Grid and distributed energy resource and load aggregation.
- Accelerating storage cost reduction and performance improvement.
- Increasing recognition by lawmakers, regulators, and policymakers of the important role that storage should play in the electricity marketplace of the future.

The report [18] also layout possible energy storage applications see Table 1.1:

Table 1.1: Categories for Energy Storage Application

Electric Supply	Electric Energy Time Shift
	Electric Supply Capacity
Ancillary Services	Load Following
	Area Regulation
	Electric Supply Reserve Capacity
	Voltage Support
Grid System	Transmission Support
	Transmission Congestion Relief
	Transmission and Distribution Upgrade Derferral
	Substation on site power
End User/Utility Customer	Time of Use Energy Cost Management
	Demand Charge Management
	Electric Service Reliability
	Electric Service Power Quality
Renewables Integration	Renewables Energy Time Shift
	Renewables Capacity Firming
	Wind Generation Grid Integration

1.1.2.1 Electric Energy Time Shift

For this work we will focus on electric energy time shift where we have used Water Heater (WH) as a storage device and have modified the heating schedule. Further specific details are in the chapters ahead. The question that I want to answer here is *"Why electric energy time shift will be a major service that needs to be provided for renewable especially PV?"*.

In case of solar generation it is obvious that the generation is dependent solely on weather and location of the installed PV and therefore, the generation happens during the daytime when the sun is up. As discussed in section 1.1.1 too much of a generation may lead to PV curtailment during the day time hours and as the day passes since the demand is still high, it can cause excessive stress on the conventional generators (like coal or natural gas fueled). Therefore, it becomes an essential for the modern or future grid to have flexible loads which can participate in demand response. Energy storage devices can offer a great help overcome this challenge as they can be treated as a load and charge during the day time hours and support the conventional generators as the day passes.

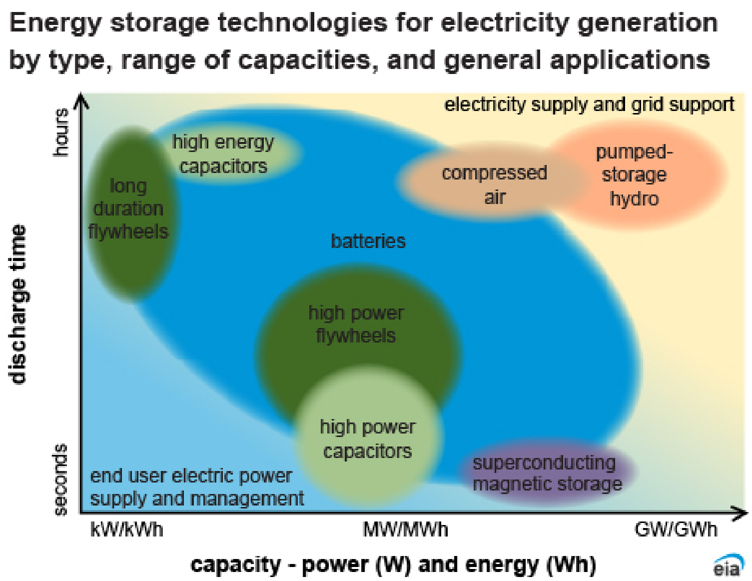
1.1.3 Technologies That Offer Energy Storage

In this section type of conventional commercially available energy storage in the USA is discussed. The electricity is used to charge the Energy Storage System (ESS) when the excess generation is available such that it can be used later when demand is high and alleviate the stress on the grid. The ESS deployment differs based on the application i.e. for power application or energy application [17].

- Power Application: The short duration (seconds to minutes) applications are referred to as power applications and primary purpose is support the grid through power injection to maintain the power grid stability. For example frequency regulation, small signal stability etc. Technology used: small battery storage, flywheel, super capacitors.

- Energy Application: These are long duration application which involve charge/discharge cycles lasting hours. These generally require high energy capacity rating. For example energy market arbitrage where one buys electricity at a lower price and sells it later at a profit. The other application is to use the charged ESS when cost of energy in the market is high. Technology used: large battery storage, pump storage hydro, compressed air etc.

Figure 1.4 shows ESSs and general applications For this work we will focus on *energy*



Source: U.S. Energy Information Administration, adapted from Energy Storage Association Note: This is a general representation of the range of capacities and duration of electricity discharge for the types of energy storage technologies for electricity generation that are currently deployed in the United States. Excludes hydrogen, which potentially could encompass the entire range of capacities and discharge times. Some types, especially batteries, include technologies with a range of capacities and applications. kW is kilowatts: H is hours, MW is megawatts; GW is gigawatts.

Figure 1.4: Energy Storage Systems

application and therefore, will be discussed further. The US utility scale energy storage systems for electricity generation is in table 1.2 [19].

Electric power grid is used as to charge most of the largest ESS, furthermore, batteries are being paired as ESSs for the renewables such as solar and wind. As of December 2022, about 3,612 MW of battery power capacity were located next to or close to solar photovoltaic and wind energy projects [19].

- Pumped storage hydroelectric systems: In these ESSs water is pumped up using electricity to fill the reservoir and released back down through turbines when required to generate electricity.

- Battery energy storage systems: As electric power markets in the USA are

Table 1.2: U.S. utility-scale energy storage systems for electricity generation, 2022

Storage system	**Number of plants and of generators**	**Power capacity MW**	**Energy capacity MWh**	**Gross generation**	**Net generation**
pumped storage hydro	40-152	22,008	NA	22,459,700	6,033,905
batteries	403-429	8,842	11,105	2,913,805	539,294
solar-thermal	2-3	405	NA	NA	NA
compressed air	1-2	110	110h	NA	57
flywheels	4-5	47	17	NA	0

Data source: U.S. Energy Information Administration, Preliminary Monthly Electric Generator Inventory (Form EIA-860m) and Power Plant Operations Report (Form EIA-923), February 2023. Note: Includes facilities with at least 1 megawatt (MW) of total nameplate capacity operational at end of 2022; MWh is megawatthours; NA is not available.

undergoing significant structural chang the report [20], large scale battery stoage was to contribute 10,000 MW to the grid between 2021 and 2023 which is 10 times the capacity in 2019.

- Compressed air storage systems: There's one compressed air energy storage system: the PowerSouth Energy Cooperative facility in Alabama which has 100 MW power capacity and 100 MWh of energy capacity. The system's total gross generation was 23,234 MWh in 2021. The facility uses grid power to compress air in a salt cavern. When needed, the pressurized air is released, heated with natural gas, and then expanded through a gas turbine to generate electricity.

Table 1.3 shows few of the disadvantages with the discussed technologies.

1.1.4 Energy shift during the shoulder season

As discussed in subsection 1.1.1 and shown in figure 1.2 due to excess generation from solar PV during the day net demand seen by the conventional generators. Now, with the energy time shift technique we want to flatten the curve. Figure 1.5 shows

Table 1.3: Disadvantages associated with the discussed technologies

Technology	**Disadvantage**
Pumped Hydro Storage	Large and specific geographical location is required with high capital cost.
	It can also affect the natural habitats and waterways.
Battery	Regulatory barriers: lack of rules and regulations to clarify the role of BESS; restrictions or lack of clarity around if and how storage can be used across generation, transmission, and distribution roles [21]
	Market barriers: Lack of markets for system services; lack of discernment in quality and quantity of services procured. [21]
	The performance of batteries degrades over time
	Concerns over how lithium and cobalt being sourced.
	Lack of awareness and poor installation may cause thermal runaways in li-ion batteries.
Compressed air storage systems	It requires specific geological conditions such as salt cavern to be installed.
	It lower efficiency due to heat loss.
	CAES also consist of multiple technologies (e.g., diabatic, adiabatic,isothermal) and some innovations are exclusive to a single technology thus dampening the combined effects. [22]

one such example for that.

1.2 Proposed Concept

This thesis explores the potential to control domestic hot WH to reduce peak demand and increase load at strategic hours. Electrically powered domestic hot water heaters come in two different varieties [23]. The most traditional type is the resistance water heater in which an electrical resistor is energized to heat water. If the water in the tank is considered to be well mixed, then the tank can be considered as a thermal capacitor. Fig. 1.6 shows how such a system functions. Water is heated whenever the resistor is energized, and the temperature $\theta_T(t)$ is controlled using hysteris control. Assuming the water is well-mixed throughout the tank, the water temperature $\theta(t)$ over time can be described as in equation (1.1) [24].

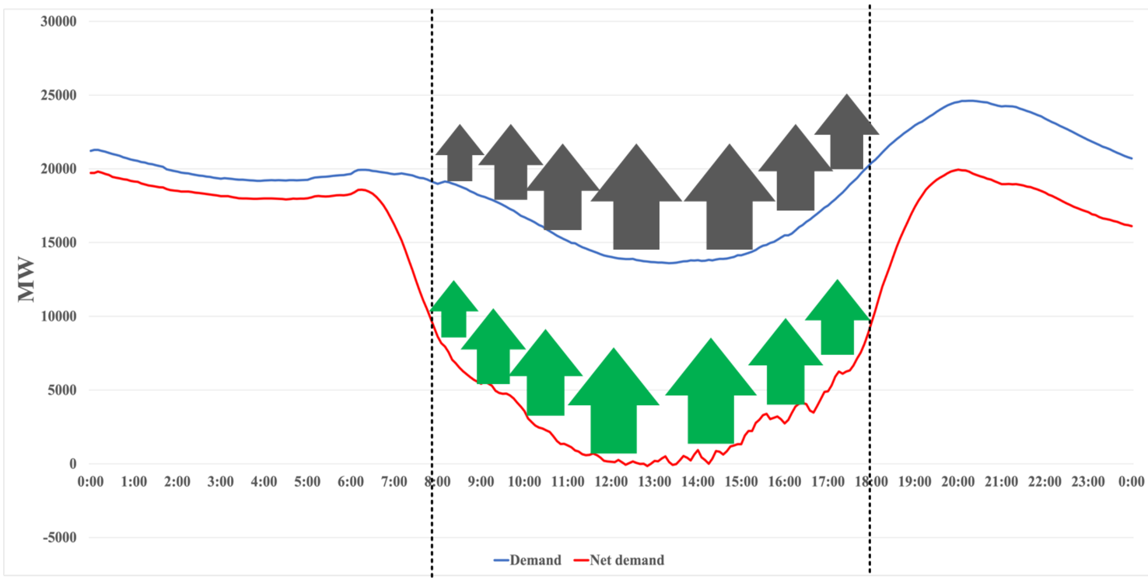


Figure 1.5: Energy Shift Concept

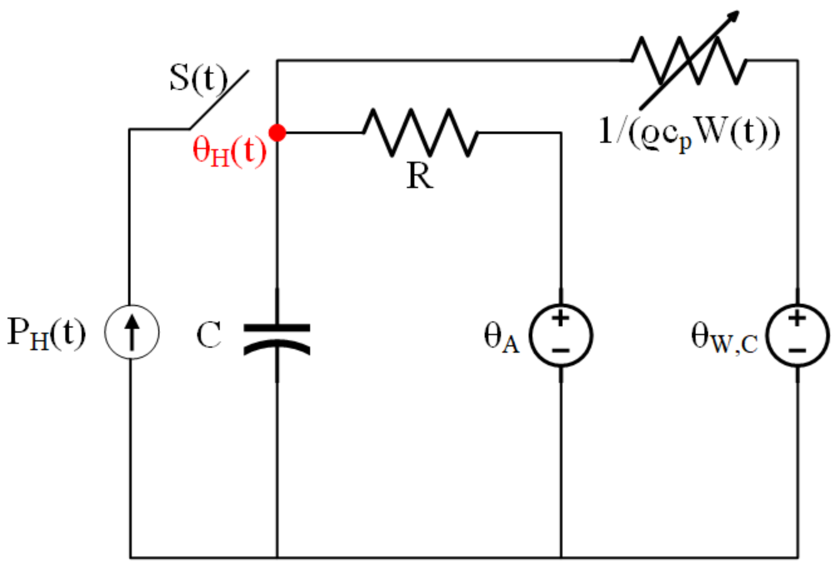


Figure 1.6: First order water heater equivalent circuit.

$$C\frac{\mathrm{d}\theta_T(t)}{\mathrm{d}t} = S(t)P_H(t) - \frac{1}{R}[\theta_T(t) - \theta_A] - \rho c_p W(t)\,[\theta_T(t) - \theta_{W,C}] \tag{1.1}$$

The control function $S(t)$ is ON/OFF status

Table 1.4: Parameters of equivalent electric water heater model

Parameter	Value or Unit
Density of water ρ	$993kg/m^3$
Specific Heat capacity of water C_p	$4179J/kg°C$
Room air temperature θ_A	$22°C$
Temperature of cold water $\theta_{W,C}$	$10°C$
Water Heater heating rate P_H	kW
Water tank volume V	50 gallon
Equiv. thermal resistance R	$1400°/kW$
Water temperature in the tank θ_T	$°C$
Hot water flow W	m^3/s

$$S(t) = \begin{cases} 0, & \text{if } S(t-1) = 1 \ \& \ \theta_T(t) \geq \theta_H(t) \\ 1, & \text{if } S(t-1) = 0 \ \& \ \theta_T(t) \leq \theta_L(t) \\ S(t-1), & \text{otherwise,} \end{cases} \tag{1.2}$$

and the thermal capacitance C is given by

$$C = V \cdot \rho \cdot c_p \tag{1.3}$$

where parameters can be defined as in Table: 1.4

Fig. 2.2 shows the normalized hourly water demand and load profile obtained from a large field study. Note that water demand, and consequently, power demand tend be concentrated in the morning and evening. Because water heaters effectively convert electrical energy into thermal energy, they can be used to convert the excess electricity from solar in the middle of the day into thermal energy that can be used at other hours. Fig. 2.2 thus describes the approach proposed in this thesis. The idea is to shift load into the middle of the day, when excess solar energy is available [25].

1.2.1 The Potential

The approach described here has significant potential to help manage grid stress because there are many water heaters in the United States. According to [12] table

1.5, there are 48.6 million electric water heaters in service in the US, which represents 42% of all the water heaters. Water heater is the second largest load of the residential customers after HVAC systems, with 11.4% of the total end use consumption in 2022 as seen from Figure 1.7 according to [5]. Similar to batteries WH is a energy storage device and it is $15kWh$ waiting to be used [12]. Water in the tank can be appropriately heated whenever power is supplied. Water has a high heat capacity, this property can be utilized and therefore, WH can he charged when excess generation is available during the day time hours even though most of the usage is concentrated during early morning and evening. Doing this may not only help in reducing the belly of the curve during the day but also reduce the ramp as well as the sun sets.

Table 1.5: US Water Heaters by Region (Millions)

	US	North-East	Mid-East	South	West
Total	115.8	21.1	25.9	42.9	25.9
Electric	48.6	5.1	8.0	28.3	7.1
Market-Share	42%	24%	31%	66%	27%

1.2.2 The Challenges Explored in this Thesis

1. Approach for effective load shifting (different size heating elements, etc.)

2. What is the upper bound techincal potential?

3. What is the impact of real usage profiles?

1.2.3 Cost of the battery storage

Table 1.6 provides the cost analysis of a battery energy storage system capable of handling the excess energy produced by the PV in order to fully flatten the curve, in California [26], having assumed that around 16% of electricity is produced through

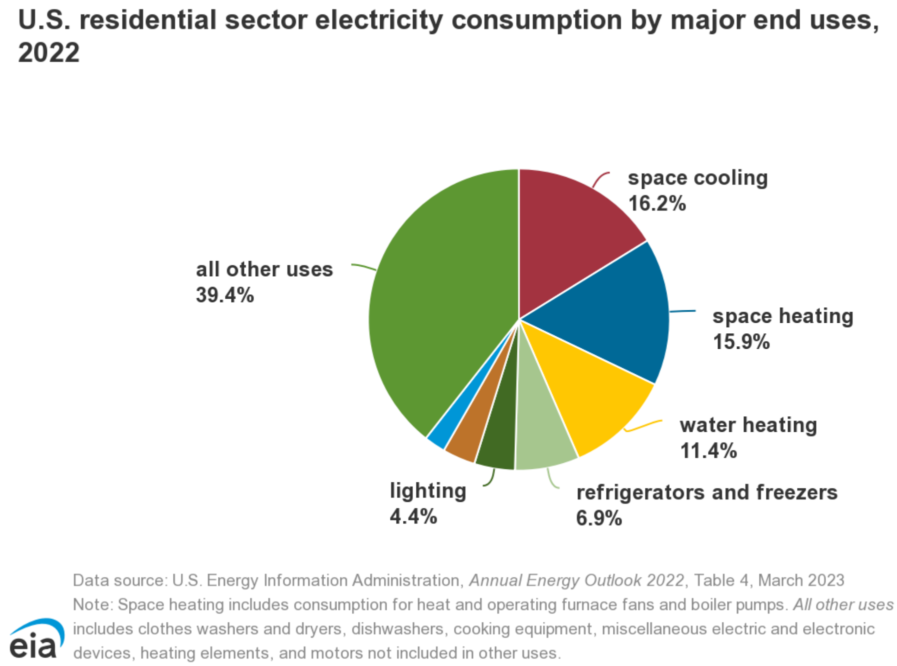


Figure 1.7: Residential Sector End Use published by EIA. [5]. Last updated: April 20, 2023

PV. According to [27], the cost of the battery cells is declining at the rate of 7% per year with a minimum cost being evaluated at 50$/kWh$ The initial capacity of the system is also over-sized to account for the natural degradation of the cells over the course of time. This analysis shows that to solve the duck curve problem using the battery mat cost up to $32.7 to $71.6 billion every 10 years.

1.3 Summary

In this document further chapters delve deep into the proposed concept of energy time shift. Chapter 2 gives the overview of why we chose domestic water heater and goes into detail of the software called energy plus developed by the Pacific Northwest National Laboratory (PNNL) and how it models the hot water heater. Chapter 3 explores what would happen if we scale the results to the whole US and discusses the scaling approach. In chapter 4 we have used actual usage data to check if our hypothesis is correct and chapter 5 provides the conclusion and possible next steps.

Table 1.6: System Cost Analysis of the battery system for solving duck curve issue

	Lithium Nickel Manganese Cobalt (NMC)		Lithium Iron Phosphate (LFP)		Lithium Titanate (LTO - LMO)	
	Best	Worst	Best	Worst	Best	Worst
Cost ($/kWh)[27][28][29][30]	180	340	180	320	260	550
EPC ($/kWh) [27]	150	180	150	180	150	180
Replacement cost ($/kWh) (10 years)[27]	90	170	90	160	130	275
Replacement cost ($/kWh) (20 years)[27]	50	85	50	80	65	138
PCS & BOP ($/kWh)[29][30]	320	590	320	590	320	590
Lifetime (Years)[27][30]	10	10	10	10	20	20
OPEX ($/kWh.year)[28][29]	91	91	91	91	91	91
Usable Capacity (GWh)	61	61	61	61	61	61
Power Rating (GW)	7	7	7	7	7	7
Capacity loss after EoL (%)	31	31	31	31	31	31
Roundtrip Efficiency (%)[27]	61	61	61	61	61	61
Evaluated Cost after 10 years (B$)	32.7	52.5	32.7	50.6	40.0	71.6
Evaluated Cost after 20 years (B$)	49.5	68.9	41.3	66.2	40.4	72.6
Evaluated Cost after 30 years (B$)	58.1	77.6	46.3	74.4	46.7	86.1

CHAPTER 2: APPROACH FOR TIME-SHIFTING DOMESTIC HOT WATER HEATING

Following the discussion in the previous section 1.2 we have utilized the domestic water heater to shift the energy during the day time hours. To follow this approach we turn on the water heater only during the day time hours and raise the water temperature using a electrical resistor element. We had to ensure at the user end this change in heating does not have an effect. Figure 1.7 shows that water heater is a major end use for the electrical energy consumption second only to HVAC.

2.1 Concept

Figure 2.1 depicts a model for the hot water heater. The cold water enters and gets heated to $65°C$ using a $0.9kW$ element between 8 a.m. to 6 p.m. The concept of using WH over HVAC is for this research is that water has a much higher heat capacity than that of air thus, water takes much longer to heat up and consequently to cool down when compared to the air therefore, it can store the energy for much longer period than air. The reason for using electric resistor water heater is that it offers $COP = 1$, i.e, it offers one to one relation between energy consumed and the work done. Figure 2.1. Figure 2.2 shows the potential of accepting the discussed energy time shift strategy.

An overview of the EP model for the hot water heater is shown in the figure 2.1

2.2 Need for a simulation tool

A comprehensive study of the approach requires a simulation tool that can capture the following:

- Realistic usage patterns.

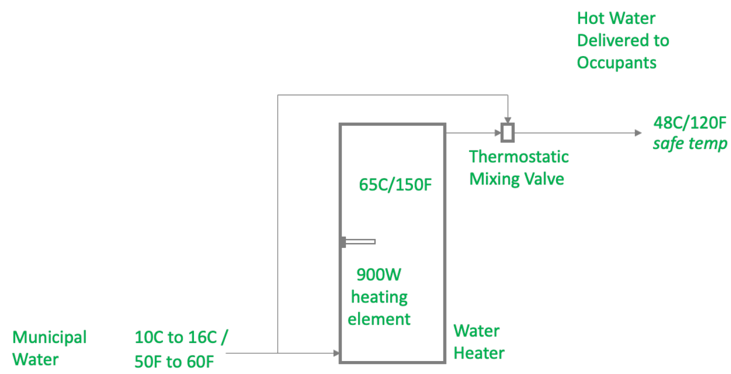


Figure 2.1: Overview of the energy plus hot water model

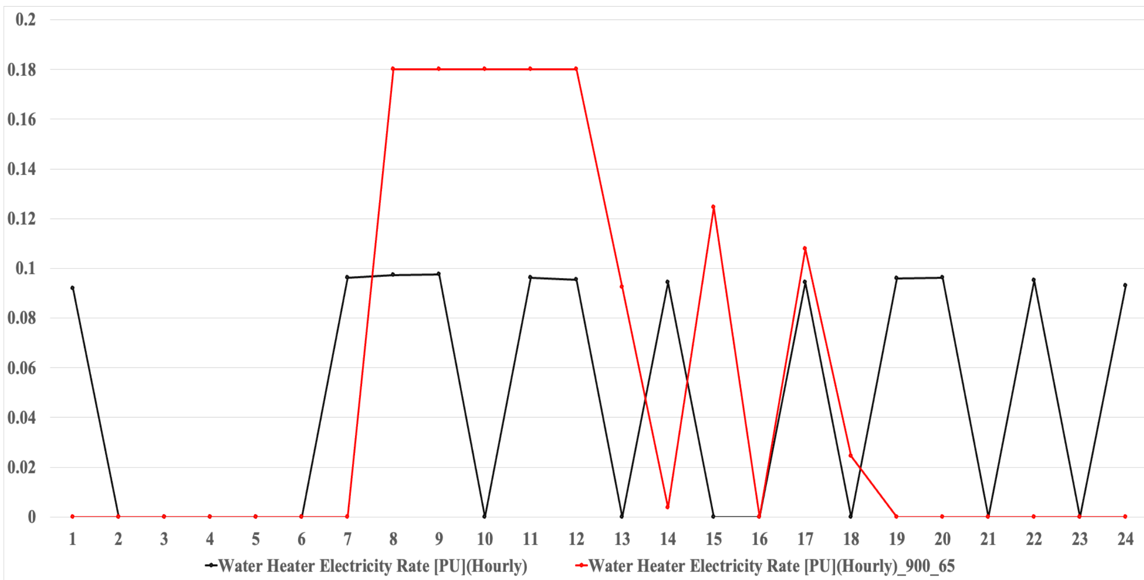


Figure 2.2: Normalized hourly water and load profile

- Realistic placement of the water heater in the different ambient conditions.

Energy plus is an ideal tool that offers the above listed features.

2.2.1 Energy Plus

This is an open-source energy simulation tool developed by the U.S Department of Energy (DOE) to model energy consumption and water use in commercial and residential buildings. Energy plus requires two files to run see figure 2.3:

1. Intermediate Data Format (IDF) file: This file has the building details such as its structural design (floor plan), construction details (insulation, exterior and

Figure 2.3: Energy Plus

Table 2.1: Weather Zones in the US

Zone	Description
2A	Hot Humid
2B	Hot Dry
3A	Warm Humid
3B	Warm Dry
3C	Warm Marine
4A	Mixed Humid
4B	Mixed Dry
4C	Mixed Marine
5A	Cool Humid
5B	Cool Dry
5C	Cool Marine
6A	Cold Humid
6B	Cold Dry
7	Very Cold

interior walls, flooring, etc.), consumer devices (HVACs, Electric Vehicles (EVs), WHs, etc.), and water systems and the use schedules.

2. Weather File: This is the Typical Meteorological Year, version 3 (TMY3) weather data file. The different climate zones in the study are according to the table 2.1.

These models are developed by PNNL. The models calculate the main line water temperature based on the weather data file which is used for the simulation. Each file describes its geographical location details in form of latitude, longitude, time zone relative to Greenwich Mean Time (GMT) and have different sizing periods.

The appendix A expounds on the discussion and gives further engineering references manual.

2.2.1.1 Energy Plus Water Heater Model

Energy plus uses “Water heater” object for storing and heating water. They can be coupled to a plant loop simulation or used stand alone. When coupled to the plant loop, the water heater has an inlet node and outlet node on the “source side” and an inlet node and outlet node on the “use side”. The source side typically draws cold water from the tank and returns warmer water, for instance, from solar hot water systems or waste heat recovery systems. The use side typically draws hot water from the tank and returns cooler water from the cold water supply mains or from the outlet of a heating system. The distinction between source and use sides is merely a convenience for reporting. They can actually be used interchangeably. If so desired, either source side or use side can be used by itself, without the other side being connected to the plant loop.

However, for a water heater that is indirectly heated (e.g. with a separate boiler), the source side can be used to provide remotely heated water to the tank. The source side is configured to operate as a component on the demand side of a plant loop. The design flow rate through the source side can be set by the user or autosized. If autosized, then a Plant Sizing object is needed elsewhere in the input file for the Plant Loop serving the source side. The water heater input includes an additional design parameter that describes how rapidly the tank can recover.

If the use side only consists of domestic hot water usage, a simple scheduled use flow rate can be specified in lieu of the full plant loop connections. The scheduled use flow rate can be used simultaneously with source side plant connections, but cannot be used with use side plant connections.

For stand-alone operation, there are no node connections to the plant loop on either source or use sides. The scheduled use flow rate determines all fluid exchange with the water tank. There are currently two water heater objects in EnergyPlus:

- WaterHeater:Mixed
- WaterHeater:Stratified

There are also compound objects that uses the WaterHeater:Mixed and/or water-Heater:Stratified as part of their strategy:

- WaterHeater:HeatPump:PumpedCondenser (WaterHeater:Mixed or WaterHeater:Stratified)
- WaterHeater:HeatPump:WrappedCondenser (WaterHeater:Stratified only)

We have used “WaterHeater:Mixed” for this work. This object simulates a well-mixed, single-node water tank offers following advantages based on the application:

- can simulate instantaneous/tankless water heaters
- requires less input than the stratified tank
- faster execution time than the stratified tank

Further details are in the appendix B.

2.2.1.1.1 Hot Water Heater: Basecase

The PNNL has modeled the houses with new heat pump water heaters which are replaced by the electric resistor water heater having the same volumetric capacity. These models are now considered as base case or default for the analysis, while any following changes to these models are termed as modified models. In the default models the water heater's electric resistor is set to auto size which EP scales to $5kW$ and the temperature of the water heater is kept as $44°C$ and the other operating conditions are kept same as before i.e, the volume of the tank is 0.196841372 m^3 (or 50 gallons). This water heater supplies several equipment namely clothes washer, dishwasher, sink, shower and bath respectively. Each of the end uses have different hot water set point and have their respective schedules. The end use cases for the water heater are shown in the figure 2.4.

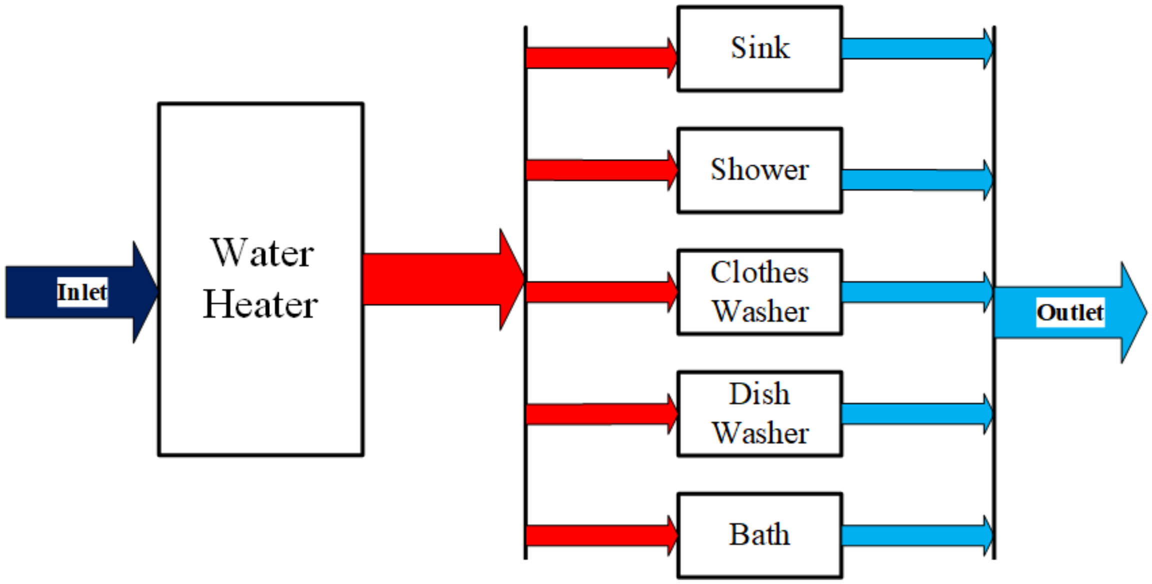


Figure 2.4: Water heater end use cases

2.2.1.1.2 Modified Energy Plus Model

For the primary analysis the schedule of the WH is modified such that it heats water in during the day time. The default temperature is changed according to the Table 2.2. It is assumed that at the end use there's a mixing valve which ensures safety of the water at the end use. Also, the WH element is changed to $0.9kW$ from the default $5kW$. It should be noted no other modifications are made to models so that each end use can keep using the water at their scheduled temperature which is essential for the accuracy analysis. Therefore, in the modified model water is being heated to $65°C/60°C$ in 8 am to 6 pm window with 0.9kW resistive element while the minimum temperature is set to $48°C$.

Table 2.2: Default and Modified Temperature Schedule

	Element Size	**Tank Temperature (8am to 6pm)**	**End Use Temperature**
Base Case	5kW	$48°C$	$48°C$
Modified Case 01	5kW	$65°C$	$48°C$
Modified Case 02	5kW	$60°C$	$48°C$
Modified Case 03	0.9kW	$65°C$	$48°C$
Modified Case 04	0.9kW	$60°C$	$48°C$

As mentioned in the Table 2.2 the temperature schedules are changed. Now, the water heater will charge the water up to $65/60°C$ during 8 am to 6 pm window and otherwise, the temperature is set to $48°C$. The figure 2.6 shows water tank temperature and power consumed to heat water in the WH tank for base case and different such scenarios. We also observe that using the 0.9kW heating element offers a smoother continuous heating over the time window compared to 5kW heating element which avoids being a continuous load over the period of 8 am to 6 pm.

2.2.1.2 How Energy Plus Models The Consumption

The usage behaviors of different loads as shown in figure 2.4 is based on the article published by NREL "Robert Henderson Building America Research Benchmark Definition, Updated December 15, 2006" [6]. In this report four major end uses were

Table 2.3: Domestic Hot-Water Consumption by End Use

End Use	**End-Use Water Temperature**	**Water Usage**	**Latent Heat Gain**
Clothes Washer	N/A	$7.5 + 2.5 * N_{br}$ gal/day (Hot Only)	0^{*}
Dish Washer	N/A	$2.5 + 0.833 * N_{br}$ gal/day (Hot Only)	0^{*}
Shower	$105°F$	$14.0 + 4.67 * N_{br}$ gal/day (Hot + Cold)	$777 + 259 * N_{br}$ Btu/day $(0.7 + 0.23 * N_{br})$ pints/day
Bath	$105°F$	$3.5 + 1.17 * N_{br}$ gal/day (Hot + Cold)	0^{**}
Sinks	$105°F$	$12.5 + 4.16 * N_{br}$ gal/day (Hot + Cold)	0^{**}

* Latent heat gains from appliances are included in the section entitled “Appliances and Miscellaneous Loads”

** Negligible compared to showers

$N_{br} = Number\,of\,bedrooms$

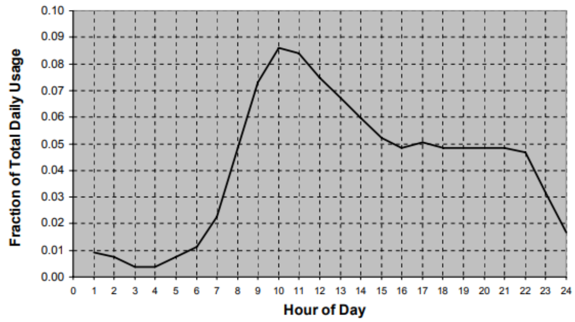
identified for domestic hot water heater see table 2.3.

For showers and sinks, the specified volume is the combined hot and cold water. This allows hot-water use to fluctuate depending on the cold water (mains) temperature. For further details kindly refer to the appendix obtained from [6].

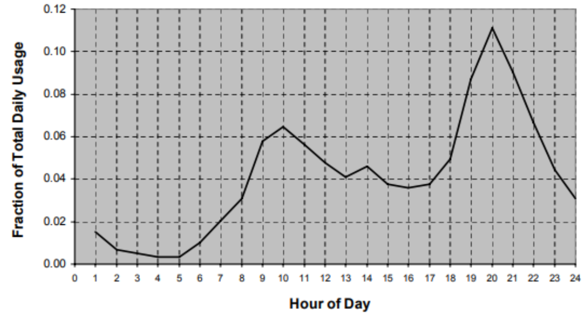
Use cases fractional usage for daily hot water is shown in figure 2.5

2.3 Result

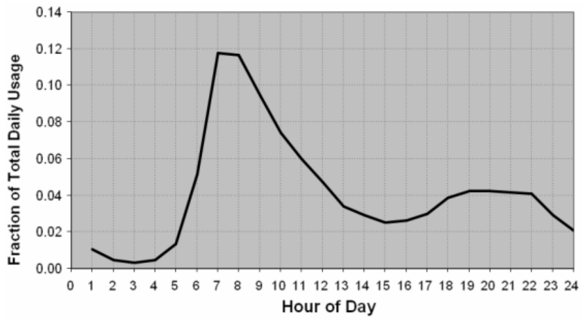
Now, with that premise we can discuss the storage potential of the water heater. Table 2.4, summarizes the storage potential for different scenarios. Here, we observed that the modified case 03 works best for us when compared to the other cases as it consumes the most and stays on throughout the required time window.



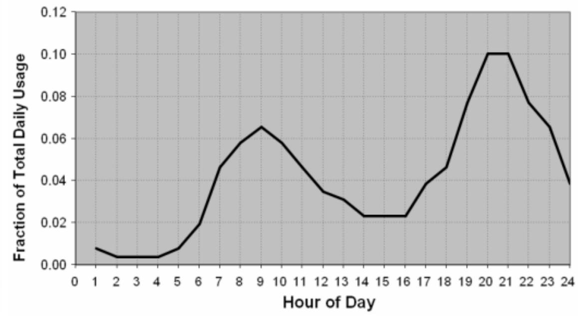
(a) Clothes washer hot-water use profile



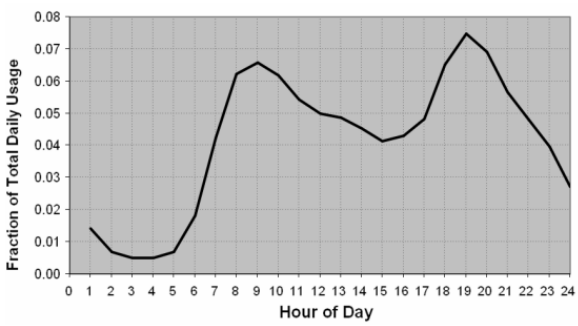
(b) Dish washer hot-water use profile



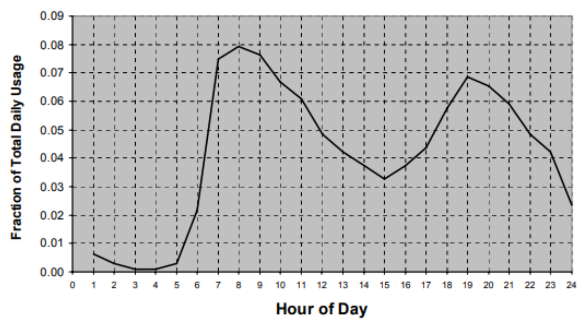
(c) Shower washer hot-water use profile



(d) Bath hot-water use profile



(e) Sink washer hot-water use profile

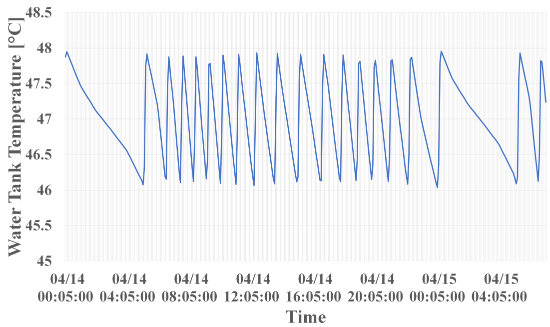


(f) Combined domestic hot-water use profile

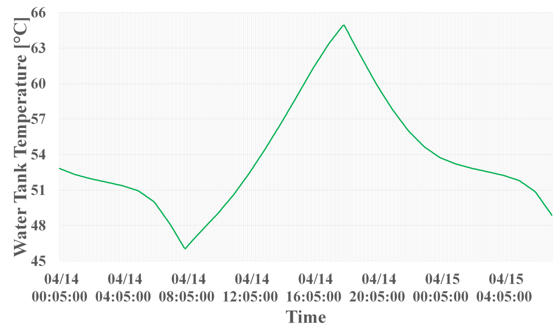
Figure 2.5: Hot Water Use-Profile as published in [6] 2003

Table 2.4: Single Home Storage Potential Case Summary

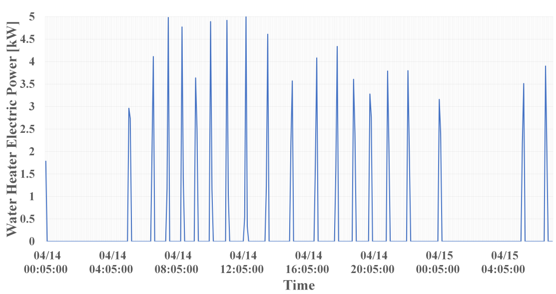
	Storage Potential	
	24hr	**8am-6pm**
Base Case	8.084	4.464
Modified Case 01	8.9718	8.9718
Modified Case 02	8.75	7.27
Modified Case 03	8.9982	8.9982
Modified Case 04	8.68	7.266



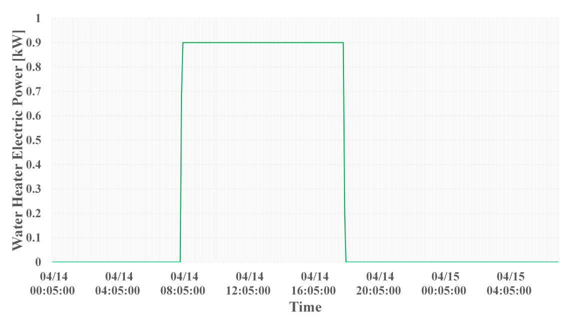
(a) Base case water temperature 48°C



(b) Modified case 03: tank temperature 65°C



(c) Power profile base case



(d) Modified case 03: 900 W heating element

Figure 2.6: Energy Plus Simulation Result with different scenarios.

CHAPTER 3: SCALING TO EXPLORE THE POTENTIAL

3.1 From Single Home To a Region

In this section we try to answer what is the storage potential in a region with the proposed idea. The results extrapolated such that if the 13 million households in the state of California used electric resistor WH in the same manner, between 34.19 and 56.55 GWh additional electric energy can be stored between the displacement time window of 8 am to 6 pm without impacting the customer side end use. This strategy would be able to displace 55% to 92% of the 61 GWh of the projected energy storage that is needed. Accordingly, the cost of the battery storage will reduce over time by the same proportion, representing $17.985 billion up to $65.872 billion (Table 1.6). Table 3.1 shows the storage potential for different scenarios compared to the base case which offers 4.64kWh storage potential for the same time window.

Table 3.1: Summary of storage potential for all modified cases compared to base case

	Water Heater Energy Consumption during 8am to 6pm [kWh]	Additional Energy Storage [GWh]	Percentage that can be displaced
Modified Case 01	8.97	56.29	92.27
Modified Case 02	7.27	34.19	56.049
Modified Case 03	8.99	56.55	92.704
Modified Case 04	7.266	34.138	56.963

3.2 Potential In The US

3.2.1 Energy Market Module

According to U.S Energy and Information Administration (EIA) publication, the Energy Market Module (EMM) of the National Energy Modelling System (NEMS) provides a 20 to 25 year forecast and analysis of energy-related activities such as the capacity planning, generation, transmission, pricing of electricity, electricity load shapes and demand, etc. To show and explain the analysis and calculations one EMM region (EMM region-20 CAMX: WECC South-West) is considered from the EMM regions 2019 shown in the figure 3.9.

3.2.2 Census Region and Census Division

- Census Region: According to EIA [31], any of the four geographic areas of the U.S. Depatrtment of Commerce, Bureau of Census. The regions each consisting of various states selected according to population size and physical location, and are shown in figure 3.8(a).

- Census Division: Each region comprises of two or three sub areas called census divisions, see figure 3.8(b)

Now, to scale the results for the US we have tried to scale the results based on the actual household end use consumption. As it is shown in 3.4, that information was available in the form of census division so we tried to map census division to the EMM region. To understand this approach first we need to look at how a particular EMM region falls under different Census Division (CD) electricity sales and different climate zones. The EIA has divided the US in 9 different CD, see figure 3.8(b) and 14 different climate zones, see table 2.1. The general idea of the process to estimate the storage potential all over US is shown in Figure 3.1.

For the first step the energy plus simulation is performed twice to get annual load profile for a climate zone 'C' to account for base case and the modified model Figure

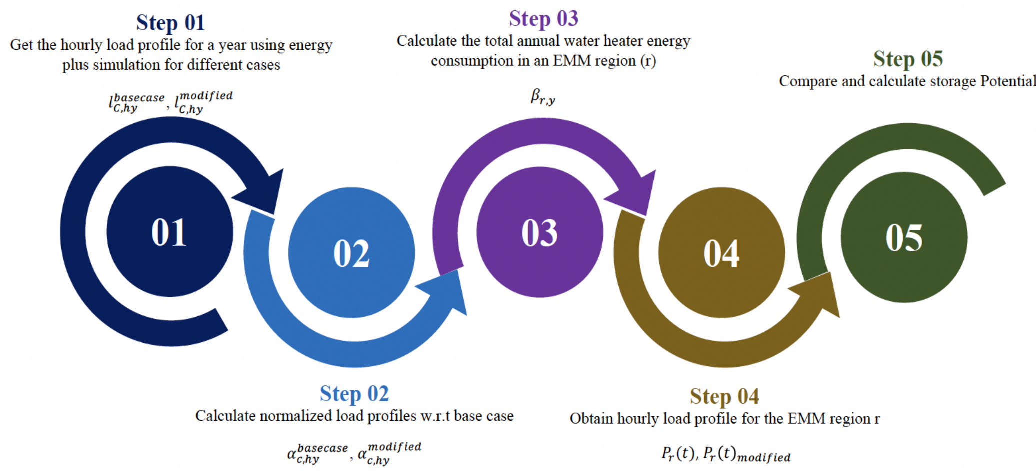


Figure 3.1: The whole US: Process

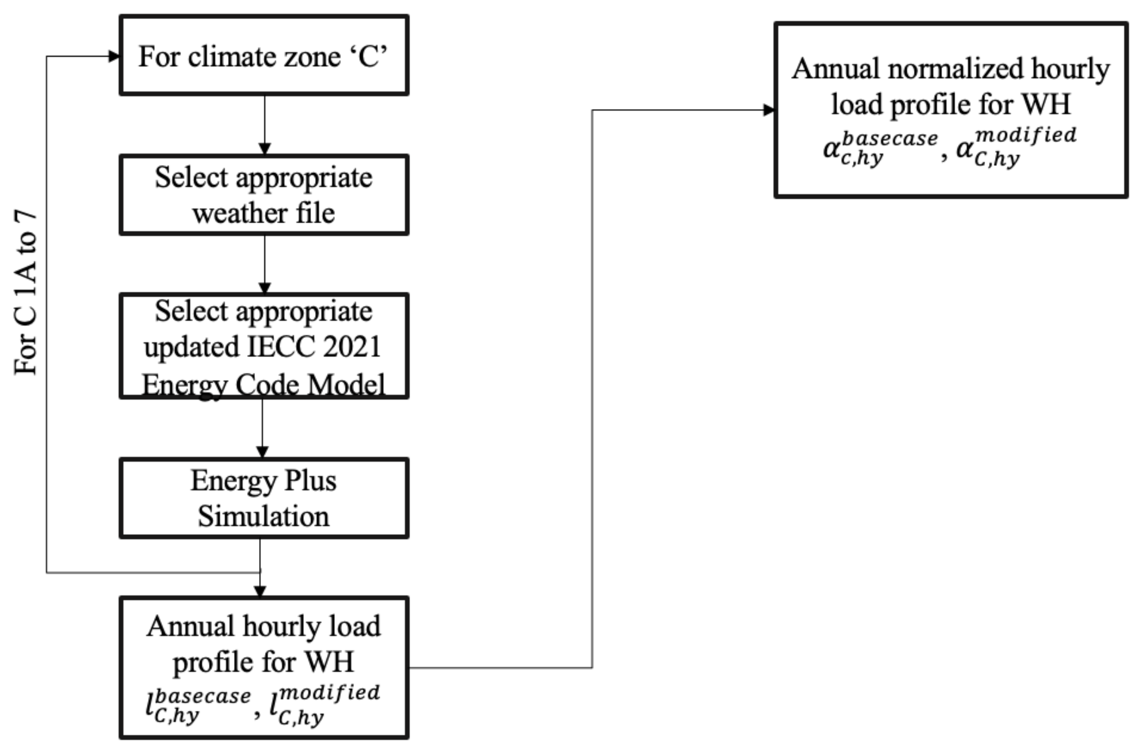


Figure 3.2: The whole US: Step 01-02

3.2. To explain it further, from table 3.4 we can see that CAMX occupies 75% of climate zones 3B, 23% of climate zone 3C, and 1% of climate zone 4B respectively [32]. Now, the next step is to calculate the normalized value of the load over the year for every hour. We use the base case models of the respective climate zones mentioned earlier and run energy plus simulations using the related TMY3 weather data for their respective energy models. Therefore, we get equation (3.1).

$$\alpha = \frac{l_{C,hy}^{basecase}}{\sum_{hy=1}^{8760} l_{C,hy}^{basecase}} \tag{3.1}$$

We perform the same exercise for the modified model such that modified normalized load profile is given by equation (3.2).

$$\alpha_{modified} = \frac{l_{C,hy}^{modified}}{\sum_{hy=1}^{8760} l_{C,hy}^{basecase}} \tag{3.2}$$

The load profile $l_{C,hy}^{basecase}$, is the load at each hour of the year where $C \rightarrow 3B,\ 3C\ \&\ 4B$ climate zones; $hy \rightarrow hour\ of\ the\ year$. This information is obtained from [32].

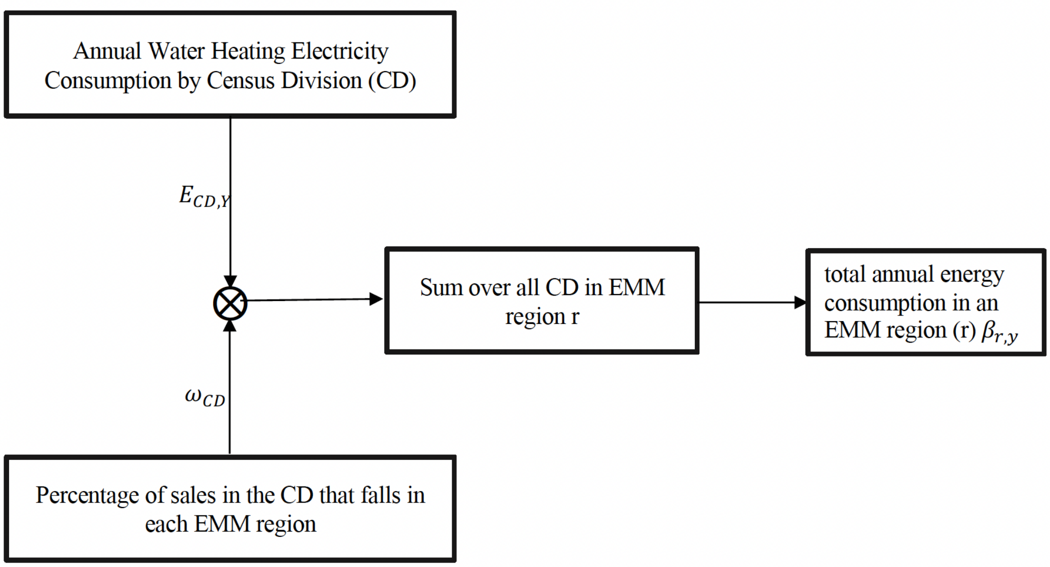


Figure 3.3: The Whole US: Step 03

The third step is to calculate the annual energy in the EMM region. To calculate

Release date: May 2018

Table CE4.1 Annual household site end-use consumption by fuel in the U.S.—totals, 2015

	Number of housing units (million)	Total site energy consumption[1]																	
		Electricity (billion kWh)						Natural gas (billion cubic feet)				Propane (million gallons)				Fuel oil/kerosene (million gallons)			
	Total U.S.[2]	Total	Space heating[3]	Water heating	Air conditioning	Refrigerators	Other[4]	Total	Space heating[3]	Water heating	Other[4]	Total	Space heating[3]	Water heating	Other[4]	Total	Space heating[3]	Water heating	Other
All homes	118.2	1,267	187	173	214	89	604	3,963	2,678	1,019	266	3,952	2,549	835	567	3,381	2,891	432	57
Census region and division																			
Northeast	21.0	172	20	21	18	14	99	895	628	206	61	869	572	175	122	2,874	2,451	390	Q
New England	5.6	42	3	6	3	4	27	158	106	42	10	365	239	79	47	1,519	1,322	175	Q
Middle Atlantic	15.4	130	17	15	15	11	72	737	522	164	51	504	333	96	75	1,356	1,129	215	Q
Midwest	26.4	252	39	30	28	20	135	1,508	1,157	297	54	1,166	887	206	73	Q	Q	N	Q
East North Central	18.1	165	25	20	18	14	89	1,115	857	212	45	695	509	Q	53	Q	Q	N	Q
West North Central	8.3	87	14	10	10	6	46	394	300	85	9	471	378	74	20	Q	Q	N	N
South	44.4	618	98	95	140	34	250	772	486	209	77	1,321	828	235	258	371	330	Q	Q
South Atlantic	23.5	316	47	52	70	18	129	385	248	102	35	740	448	118	Q	355	314	Q	Q
East South Central	7.2	105	21	19	18	5	41	117	76	27	14	223	166	37	19	Q	Q	N	N
West South Central	13.8	197	29	24	53	11	80	270	162	81	28	358	214	80	64	Q	Q	N	N
West	26.4	225	30	27	28	20	120	787	407	307	73	595	262	218	115	74	51	Q	Q
Mountain	8.5	80	8	7	15	7	43	375	241	116	18	278	124	100	Q	N	N	N	N
Mountain North	4.2	36	4	3	3	3	22	253	170	75	8	123	Q	Q	Q	N	N	N	N
Mountain South	4.3	45	4	4	12	3	21	122	71	41	10	155	Q	79	29	N	N	N	N
Pacific	17.9	145	22	20	13	14	76	413	167	191	55	317	138	118	61	74	51	Q	Q
Census urban/rural classification[5]																			
Urban	94.7	935	117	116	172	69	461	3,578	2,396	939	242	983	566	222	196	2,296	1,965	300	Q
Urbanized area	82.2	804	95	97	153	60	399	3,151	2,093	837	221	783	423	184	176	1,925	1,634	260	Q
Urban cluster	12.5	131	21	20	19	9	62	427	304	102	22	200	143	38	19	371	331	Q	N
Rural	23.5	332	70	57	42	20	143	385	282	80	23	2,968	1,984	613	372	1,085	926	132	Q
Metropolitan or micropolitan statistical area																			
In metropolitan statistical area	98.5	1,019	134	129	182	74	500	3,503	2,340	919	244	2,700	1,664	644	392	2,494	2,116	330	48
In micropolitan statistical area	12.3	155	35	27	18	9	65	319	235	67	17	552	383	86	82	380	345	Q	Q
Not in metropolitan or micropolitan statistical area	7.4	93	18	17	14	5	39	141	103	33	5	700	502	105	93	Q	Q	71	Q
Climate region[6]																			
Very cold/Cold	42.5	379	53	46	32	31	216	2,253	1,668	481	105	1,919	1,307	437	175	2,200	1,949	215	Q
Mixed-humid	33.5	412	79	63	64	25	181	986	684	236	65	1,490	1,005	209	277	1,156	922	217	Q
Mixed-dry/Hot-dry	12.7	97	6	7	22	10	53	319	117	154	48	162	49	84	29	Q	Q	N	N
Hot-humid	22.8	315	36	44	95	18	122	262	138	88	36	221	99	64	58	Q	Q	N	N
Marine	6.7	64	13	12	2	5	32	143	71	60	12	Q	Q	Q	29	Q	Q	N	Q

U.S. Energy Information Administration
2015 Residential Energy Consumption Survey: Energy Consumption and Expenditures Tables

Figure 3.4: Total Electricity sales in Census Division

this, first we multiply the percentage of electricity sales (ω_{cd}) of the census divisions that makeup the EMM region and sum them together as per equation (3.3). See figure 3.3 and 3.5 for better understanding. You can find total electricity sales in the census division in figure 3.4.

$$\beta_{r,y} = \sum_{CD} E_{CD,y} \times \omega_{cd} \tag{3.3}$$

where $\beta_{r,y}$ is the annual energy in an EMM region 'r', and $'E'_{CD,y}$ is the annual energy consumption in the census division. For our case EMM region 20 CAMX occupies 59% of census division 9 electricity sales (refer to Table 3.3)

Therefore, to obtain the hourly load profile for the EMM region 'r' ($r = 20(CAMX)$), equation (3.4).

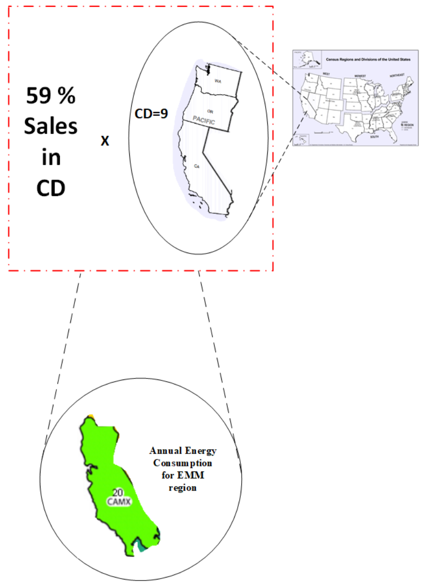


Figure 3.5: Annual Energy Consumption for the CAMX EMM region

$$P_r(t) = (\beta_{r,y}) \times \sum_C \alpha \times \omega_C \tag{3.4}$$

where $\omega_C \to 0.75, 0.23, 0.1$

Similarly, we can obtain the modified load profile for the EMM region 'r' ($r = 20(CAMX)$), equation (3.5).

$$P_r(t)_{modified} = (\beta_{r,y}) \times \sum_C \alpha_{modified} \times \omega_C \tag{3.5}$$

Now, we have everything to compute the hourly change in the energy in the specific EMM region 'r' between the modified and base case scenarios, using equation (3.6). The figure 3.6 shows the following step. Result for one day of CAMX is plotted in figure 3.7 that shows 19.80368 GWh of storage potential over 8am to 6pm and for the regions all the results are summarized in the table 3.2.

$$\Delta EMM_r = P_r(t)_{modified} - P_r(t) \tag{3.6}$$

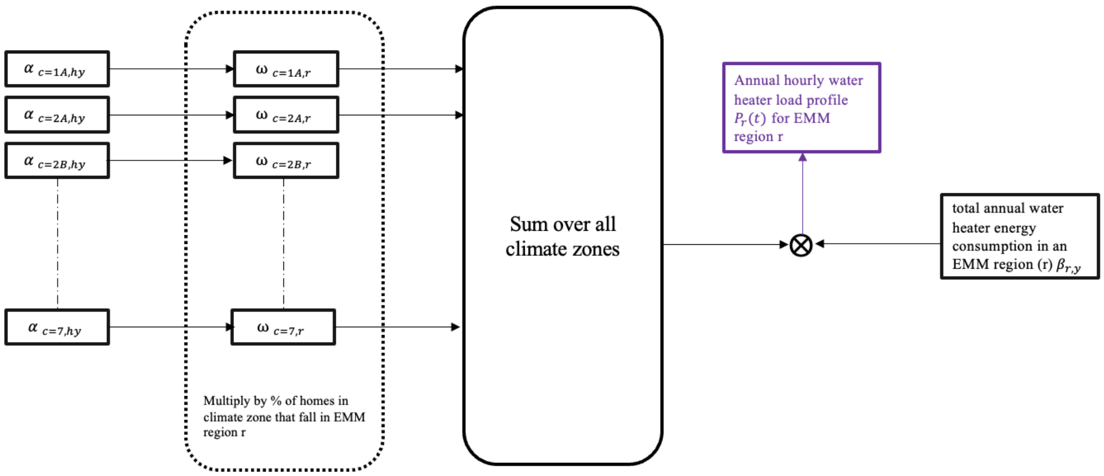


Figure 3.6: The whole US: Step 04

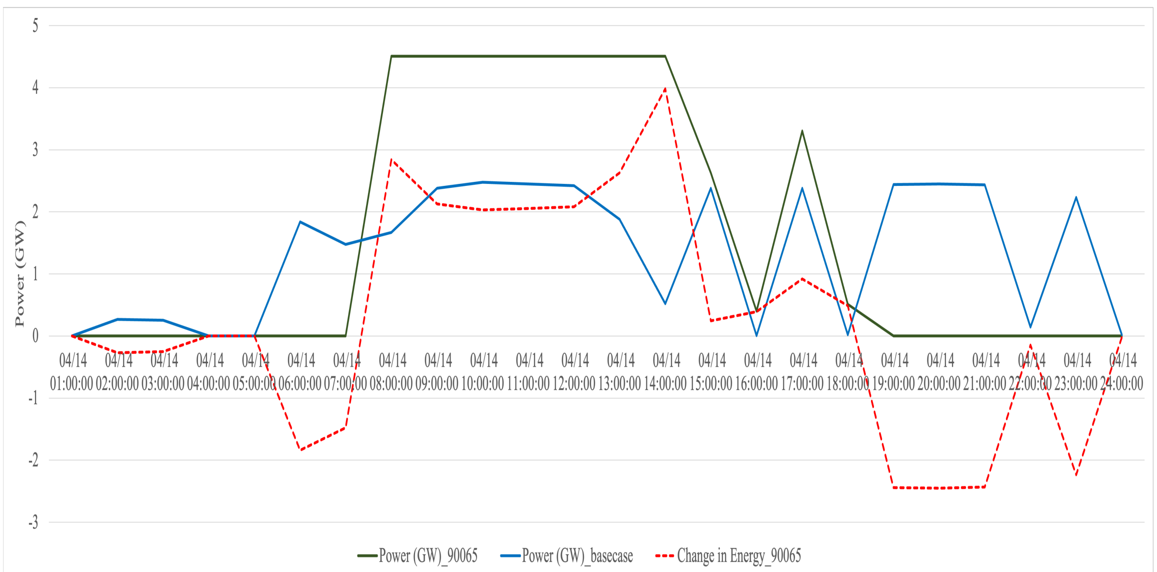
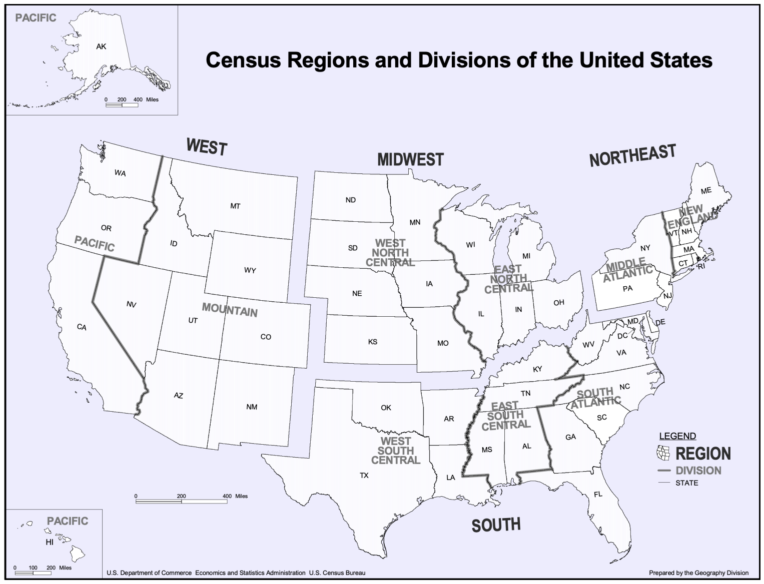


Figure 3.7: EMM region CAMX one day power profile

Table 3.2: EMM Region Summary

S.No.	EMM Region	Energy for 8AM to 6PM 900_65 (GWh)	Energy base case for 8AM to 6PM (GWh)	Energy Storage Potential for 8AM to 6PM (GWh)
1	ERCT	47.9583	22.899	25.0589
2	FRCC	55.6071	25.2585	30.3486
3	MROE	2.824	1.868	0.95629
4	MROW	16.644	9.9654	6.6787
5	NEWE	18.228	10.335	7.8926
6	NYCW	4.335	2.348	1.987
7	NYLI	2.8939	1.566	1.327
8	NYUP	10.3667	5.9586	4.408
9	RFCE	186.668	102.28	84.38
10	RFCM	31.18	17.544	13.63
11	RFCW	56.655	31.7030	24.952
12	SRDA	20.3993	9.8039	10.59
13	SRGW	13.3353	7.281	6.054
14	SRSE	47.3504	23.912	23.4382
15	SRCE	42.1999	22.5796	19.6202
16	SRVC	62.1211	32.8	29.3207
17	SPNO	6.679	3.612	3.067
18	SPSO	16.672	8.404	8.268
19	AZNM	13.2768	6.2795	6.997
20	CAMX	38.3925	18.591	19.80368
21	NWPP	28.897	10.825	18.072
22	RMPA	4.929	2.767	2.16215



(a) Census Regions

U.S. Census Bureau

Census Bureau Regions and Divisions with State FIPS Codes

Region I: Northeast

Division I: New England

Connecticut (09)
Maine (23)
Massachusetts (25)
New Hampshire (33)
Rhode Island (44)
Vermont (50)

Division 2: Middle Atlantic

New Jersey (34)
New York (36)
Pennsylvania (42)

Region 2: Midwest*

Division 3: East North Central

Indiana (18)
Illinois (17)
Michigan (26)
Ohio (39)
Wisconsin (55)

Division 4: West North Central

Iowa (19)
Kansas (20)
Minnesota (27)
Missouri (29)
Nebraska (31)
North Dakota (38)
South Dakota (46)

Region 3: South

Division 5: South Atlantic

Delaware (10)
District of Columbia (11)
Florida (12)
Georgia (13)
Maryland (24)
North Carolina (37)
South Carolina (45)
Virginia (51)
West Virginia (54)

Division 6: East South Central

Alabama (01)
Kentucky (21)
Mississippi (28)
Tennessee (47)

Division 7: West South Central

Arkansas (05)
Louisiana (22)
Oklahoma (40)
Texas (48)

Region 4: West

Division 8: Mountain

Arizona (04)
Colorado (08)
Idaho (16)
New Mexico (35)
Montana (30)
Utah (49)
Nevada (32)
Wyoming (56)

Division 9: Pacific

Alaska (02)
California (06)
Hawaii (15)
Oregon (41)
Washington (53)

**Prior to June 1984, the Midwest Region was designated as the North Central Region.*

(b) Census Divisions

Figure 3.8: Census Region and Census Division

Figure 3.9: EMM Regions 2019 published by EIA [7]. Release date: February 2019

Table 3.3: Percentage of residential building sales in each of the nine U.S Census Divisions (columns) that falls in each of the 22 2019 EIA EMM regions rows

		Census Division								
		1	2	3	4	5	6	7	8	9
EMM Region	1							59		
	2					32				
	3			5						
	4			3	52					
	5	100								
	6		9							
	7		6							
	8		23							
	9		51			9				
	10			17						
	11		10	66		6	3			
	12						7	20		
	13			9	24					
	14					17	25			
	15					1	65			
	16					34				
	17				21					
	18				1			20	1	
	19							1	50	1
	20									59
	21								28	37
	22				1				21	

Table 3.4: Mapping between ASHRAE90.1-2016 regions used for EP simulations and EIA EMM regions. This is the perecentage of a given EMM region's population that falls into a given ASHRAE region (note: not all rows sum to 100 due to rounding)

EMM Region	ASHRAE 90.1-2016 Region														
	1A	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	5C	6A	6B	7
ERCT		60	2	34	4										
FRCC	24	76													
MROE										3			88		9
MROW										36			52		11
NEWE										84			16		
NYCW							97			3					
NYLI							100								
NYUP											70		30		
RFCE							62			36			1		
RFCM										92			8		
RFCW							17			75			8		
SRDA		60		38			2								
SRGW							71			29					
SRSE		16		78			6								
SRCE				21			79			1					
SRVC				44			56								
SPNO				4			90			5					
SPSO		9		75	8		1	8							
AZNM			43		43			8			7				
CAMX					75	23		1							
NWPP					1				50		35	1		13	
RMPA								1		1	88		3	4	3

CHAPTER 4: USING REAL DEMAND PROFILES

In theory the above analysis looks good but it is required to check if the same will hold true in real usage scenarios. Therefore, this method is implemented on different type of houses with different usage patterns according to Table 4.1. In North Carolina according to Duke Energy Progress East (CPLE) the generation from the renewable has been increased and thus, resulted into over-generation which has lead to a lower net demand. This can be seen by the Figure 4.1

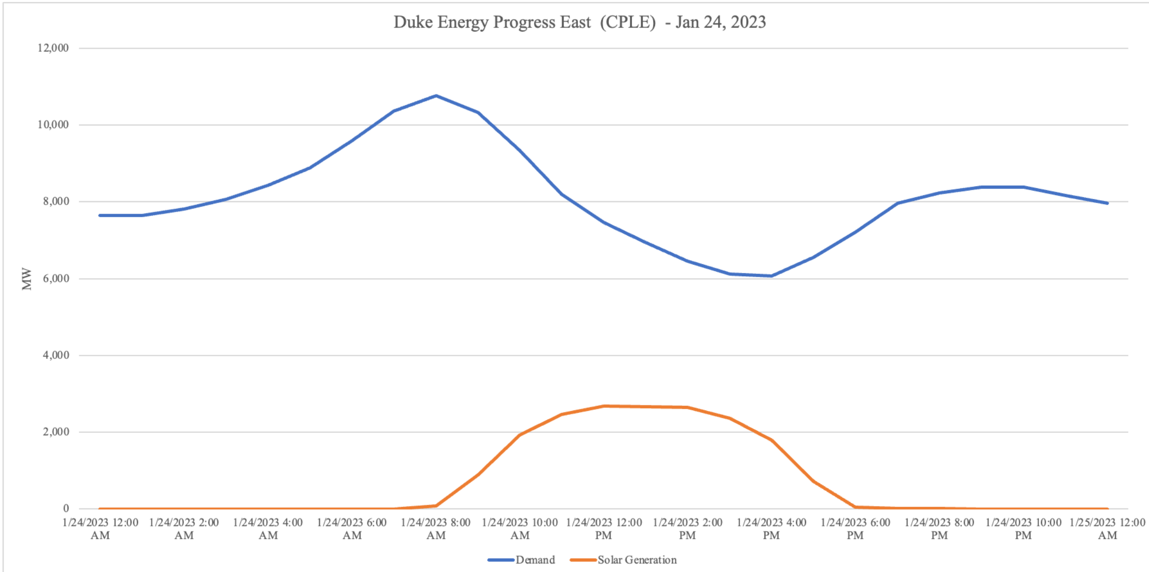
4.1 Scaling Process

4.1.1 Data Used

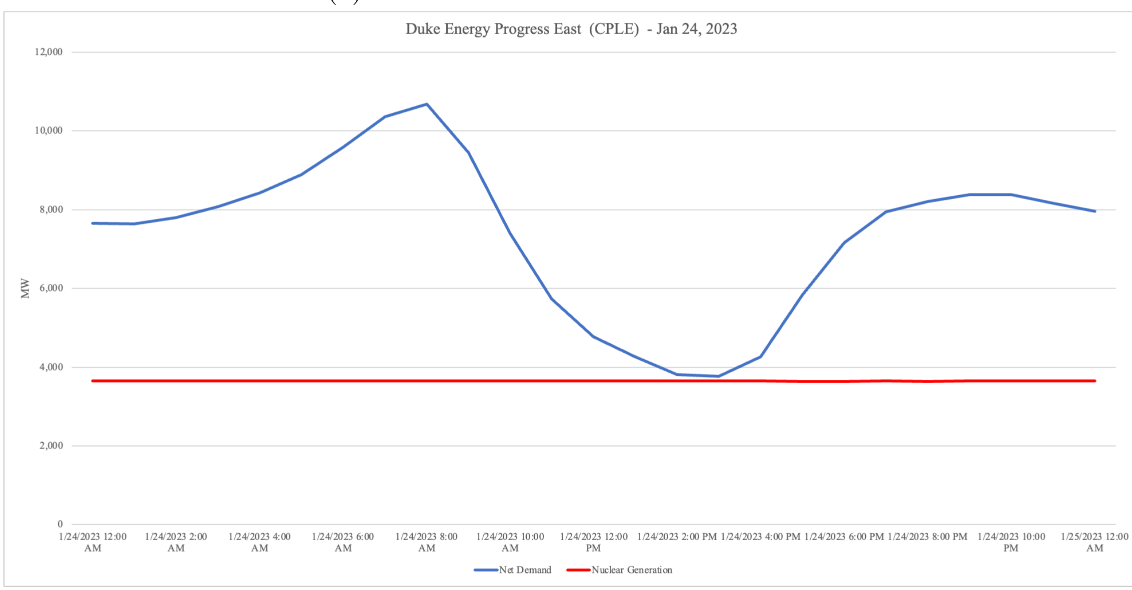
This analysis is accomplished with the joint collaboration of mathematics department and EPIC at UNCC. For this analysis one data set is obtained from 73 houses in Qubec, Canada [33]. The data is divided into 4 house types each with different usage profiles; for this analysis we have only used the data for average and sparing consumption level as shown in the Table 4.1. The data files for the consumption patterns named after the house numbers.

Table 4.1: House Types

Consumption Level	Consumption Pattern	House Number	Number of occupants	Annual Averaged Daily Consumption (lit)
Average	Morning	House 38	3	176
	Evening	House 14	3	189
	Dispersed	House 73	3	182
Sparing	Morning	House 11	2	116
	Evening	House 43	3	116
	Dispersed	House 16	n/a	124



(a) CPLE demand and solar Generation



(b) CPLE net demand and nuclear generation

Figure 4.1: Impact of renewable in North Carolina

[33] created annual Daily Hot Water (DHW) consumption profiles at a time resolution of 5 minutes interval for four consumption levels and three temporal consumption patterns. The measurement and data analysis employed to generate the hot water draw profiles are shown in the same article.

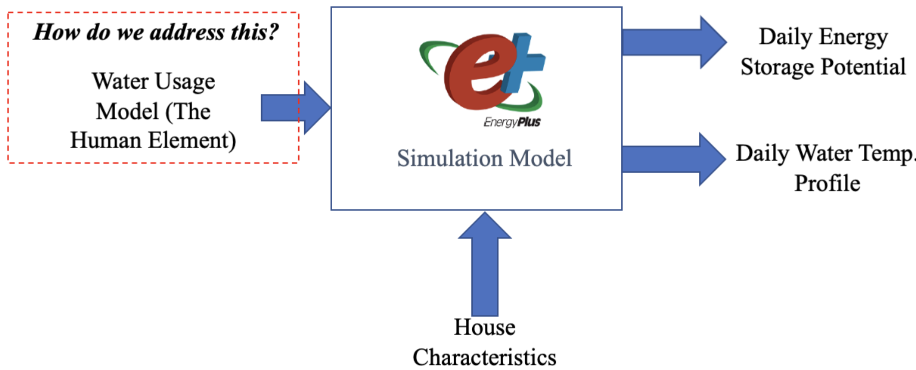


Figure 4.2: Overall Approach for analysis 03

4.1.2 Simulation Approach

A probabilistic data driven model is developed to simulate hot water usage profile in a 15 minute time frame for each household throughout the week. The overall model relies on two sub models:

- Probabilistic model to estimate the necessary parameters required for the simulation framework.
- Simulation algorithm using the estimated parameters to create randomly simulated sample of hot water profile of the type of household data used.

The output data produced by this model is then used in EP model which has a five minute time stamp and the hot water consumed in the respective time stamp for a certain weekday throughout the year. The overall approach is shown in Figure 4.2.

For the reference there are 333,327 single family homes in Wake County, NC [34]. If each house absorbs 9kWh of energy on a day of high solar generation, around 3000 MWh could be stored which is about 17% of the CPLE's daily solar generation.

The model can be used to generate an arbitrary number of hot water profiles. **Hundred thousand** simulations for each house types were performed to imitate the random usage behavior for their respective house type. Figure 4.5 shows one such example. It should be noted that these water profiles include the consumption of all

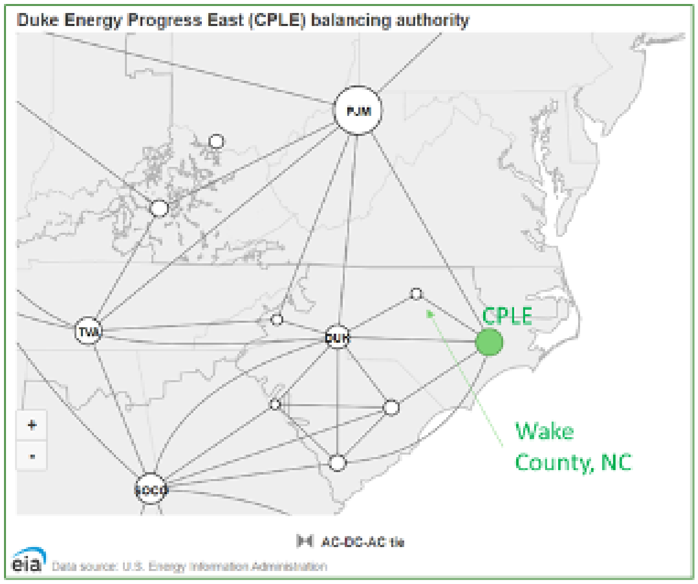


Figure 4.3: CPLE and Wake county

the end uses therefore, for EP models were modified to imitate such behavior (See Figure 4.4).

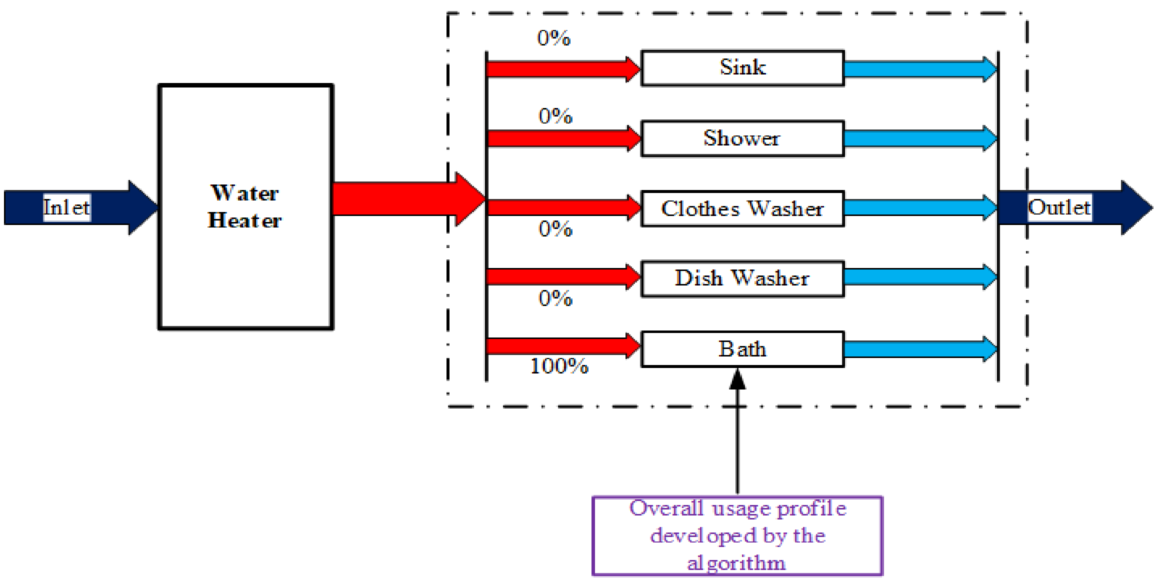
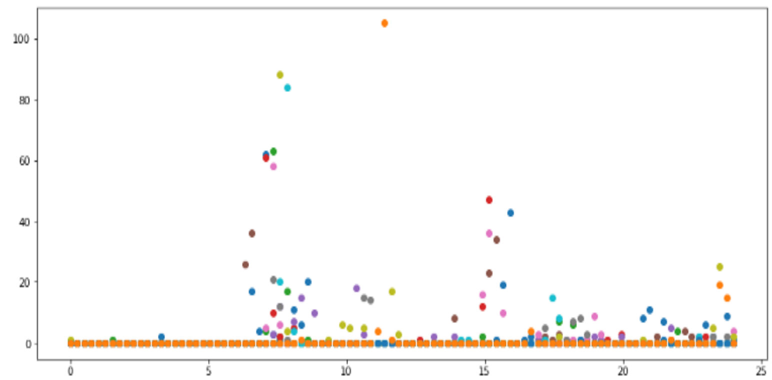
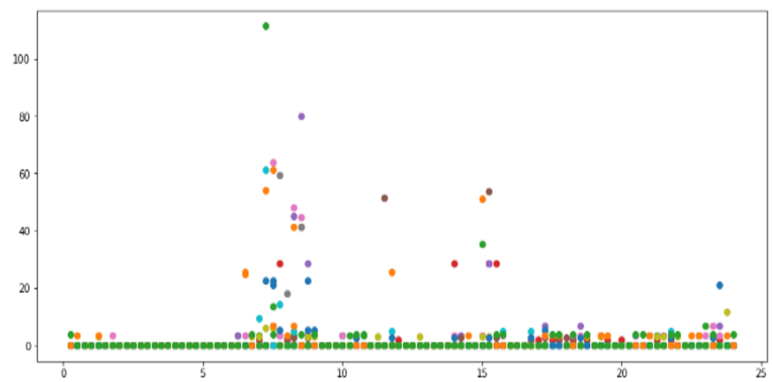


Figure 4.4: Energy Plus modified model



(a) Measured Data



(b) Modeled Data

Figure 4.5: Top: The hot water consumption profile for Mondays in Winter (Jan, Feb, March) from the dataset; Bottom: The hot water consumption profile for Mondays in Winter (Jan, Feb, March) from the algorithm

Figure 4.6 shows hot water temperature and gallons of the used for the entire week. It can be observed when the model is initialized, the water heater temperature is at $120°F$, it then climbs to $150°F$ during the energy storage period. This particular house was a low usage home, the hot water temperature, on most days did not fall back to $120°F$ before the storage period next day. This limits the amount of energy storage potential of this home. In addition, even though this home is a low user, we see that on one day, hot water almost ran out during a high-usage event. This is exactly sort of behavior that we expected to observe and account for.

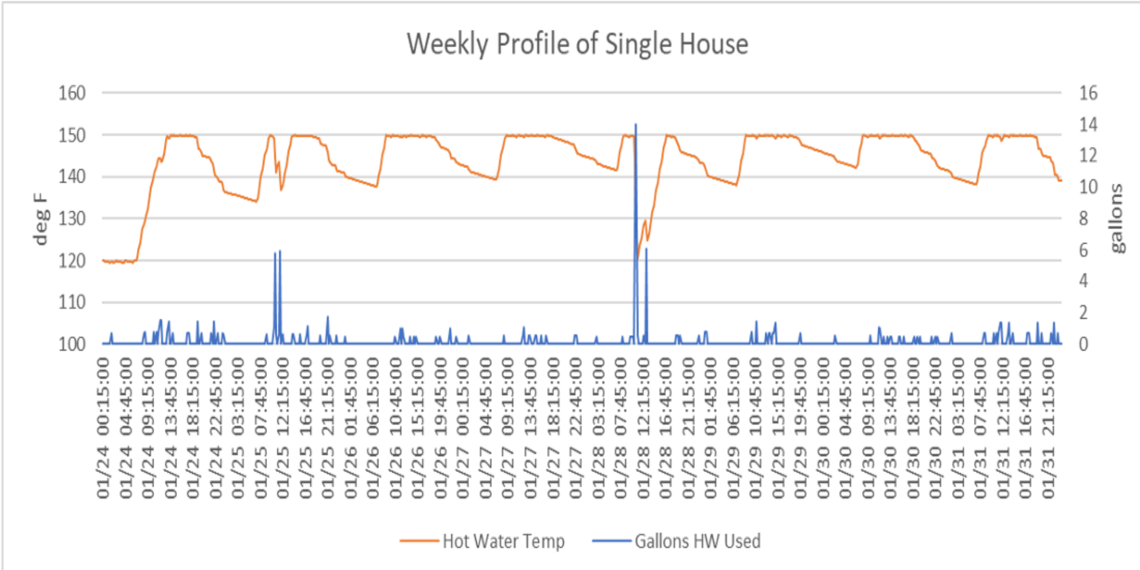


Figure 4.6: Hot water profile for a week

4.2 Simulation Results

Now, transitioning from a single home to the results of large number of homes, city/regional scale. Thus we can answer some essential questions, the first of which is how many homes ran out of water. Figure 4.7 sheds light on that question, we can see average houses ran out of hot water most of the time compared to sparing usage houses.

The graph in figure 4.8 shows the histogram of the daily storage of the low usage homes. The take away here is that our results are showing an average of about 5kWh of storage for this house type; with a significant number of homes with much less than that (see the tail extending left of the mean).

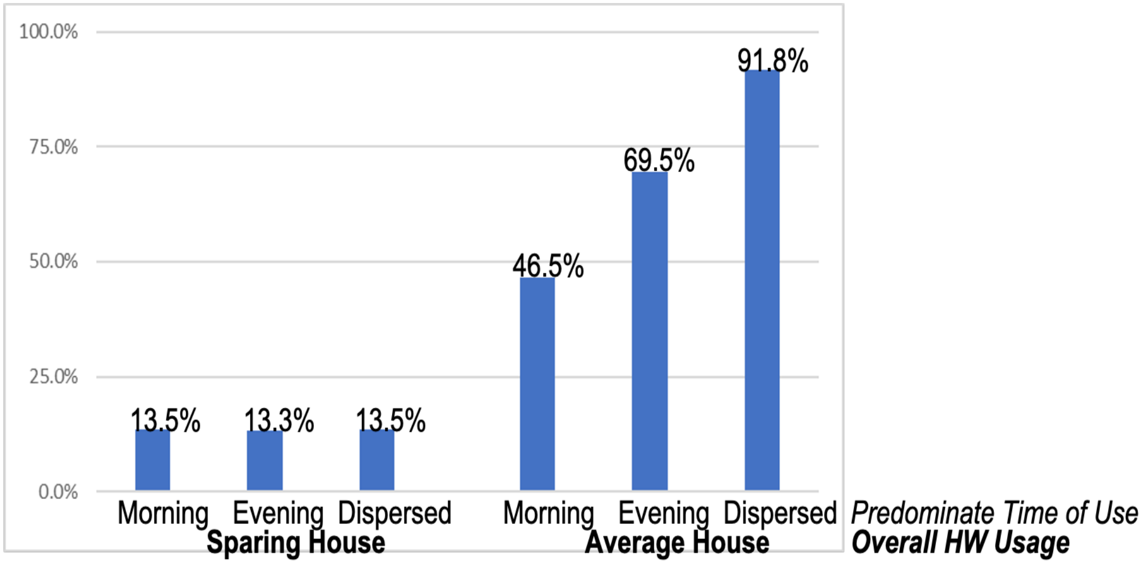


Figure 4.7: Percentage of houses that ran out of hot water

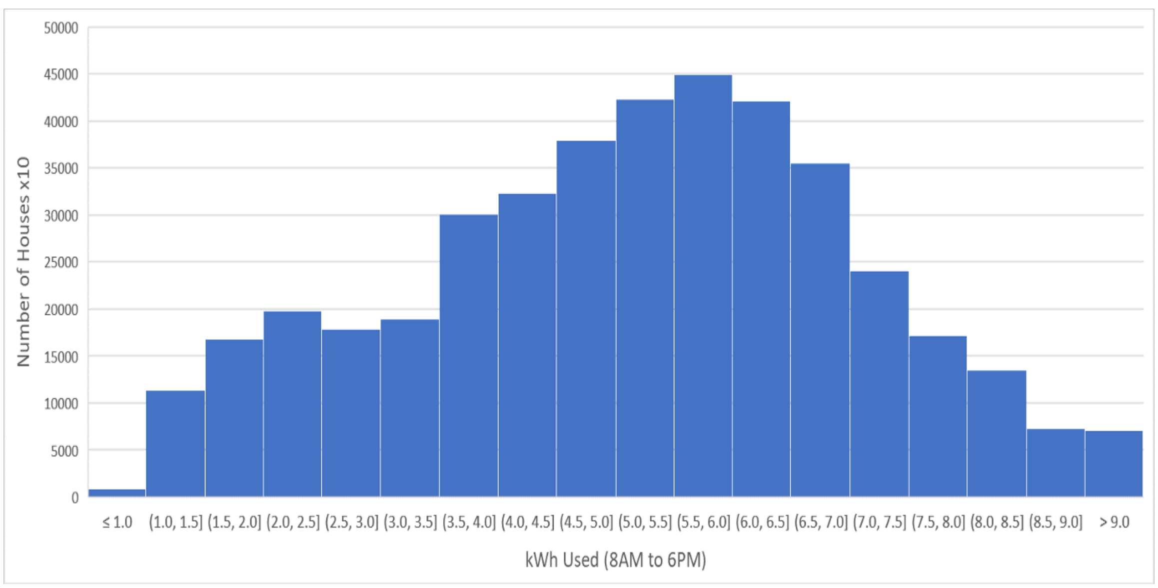


Figure 4.8: Histogram: Daily Storage of the low usage homes

Now, we look at the average usage homes, the histogram is a bit more normal in its shape. Overall, the average storage potential is slightly higher, at about 5.5kWh to 6kWh per day though significantly less than the baseline model.

In summary, we know that in reality , hot water is used in discretely over the day. Sometimes these events use significant amounts of hot water, shower or laundry.

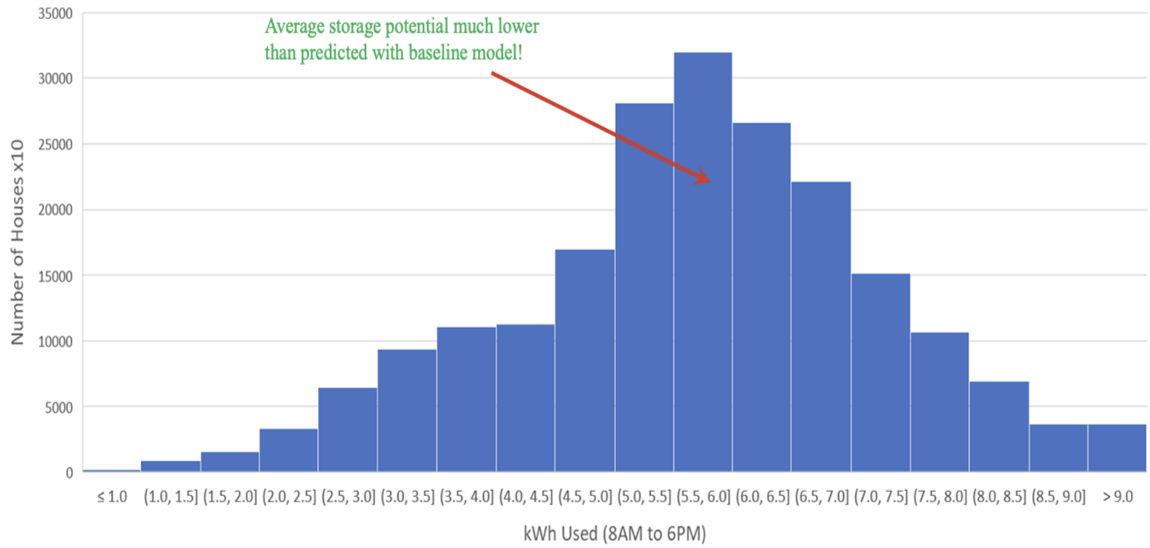
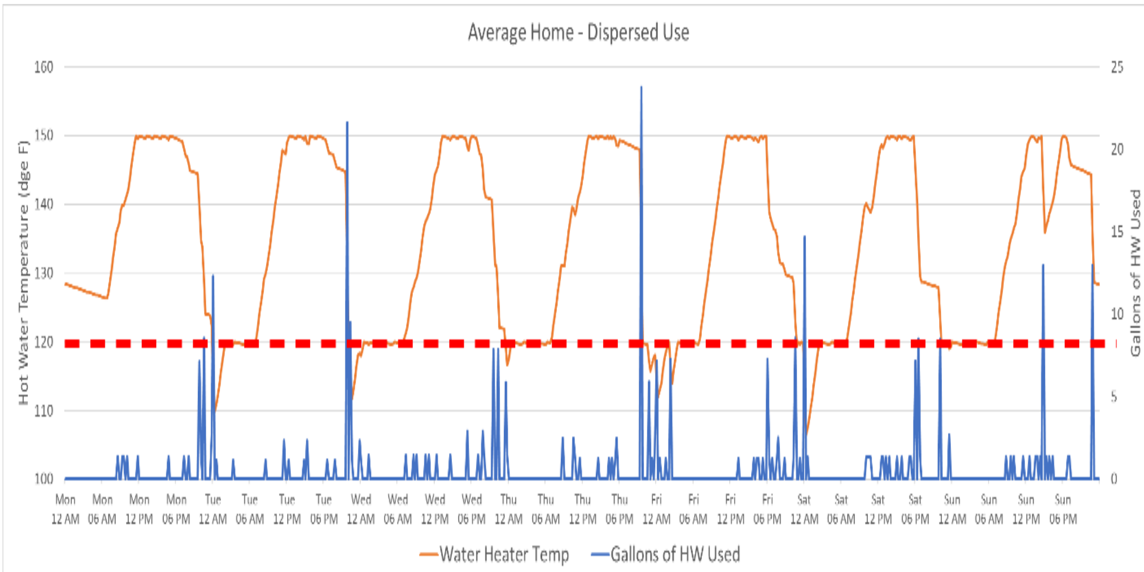


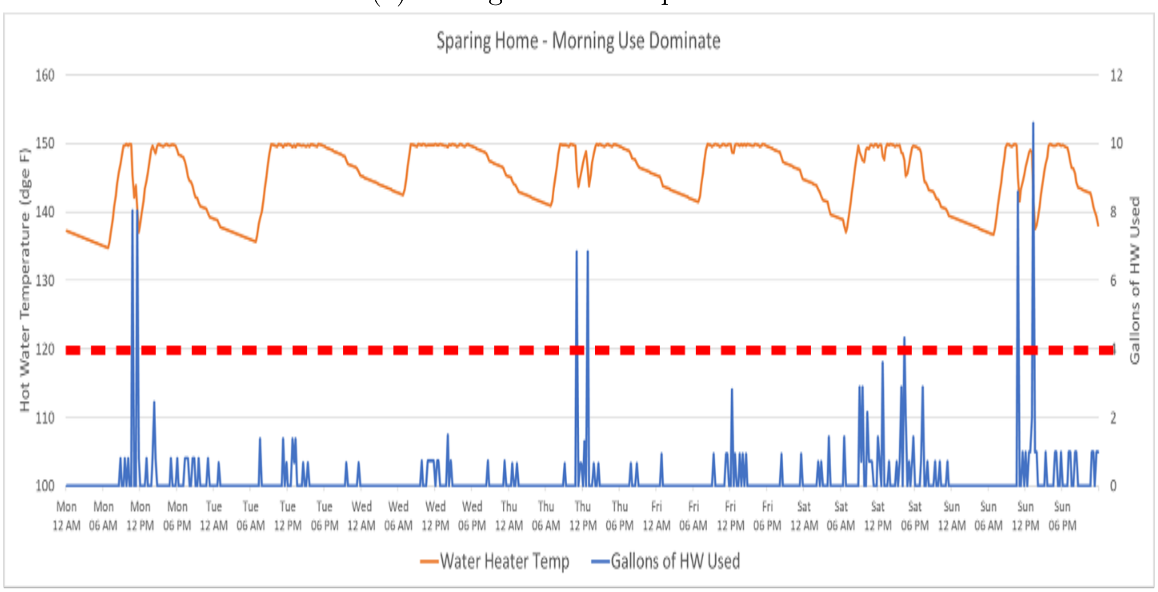
Figure 4.9: Histogram: Daily Storage of the average usage homes

Some days, not much hot water is used at all. These behavior elements affect the potential of that they can cause hot water shortage, on one hand, and limited storage potential, on the other.

Here, we have a weekly graph in Figure 4.10 for an average home on top which offers higher storage potential but would not be a seamless experience for the homeowner. On the bottom, for a low-usage home, the home owner may not experience any difference, but the storage potential is limited.



(a) Average Home: Dispersed Use



(b) Sparing Homes: Morning Use

Figure 4.10: One week Usage Profile

CHAPTER 5: CONCLUSIONS

The approach in theory shows merit however, with realistic user models changes the narrative. It is critically important to create realistic models of the user behavior. We can use Advanced Metering Infrastructure (AMI) data to create a realistic data set to achieve better accuracy. Additional auxiliary heating elements might be needed to overcome the loss of hot water throughout the day.

With the city/regional scale modeling infrastructure that we have developed, we can begin to through and integrate an optimal control strategy for a population of water heaters. We also may need to think rethink the optimal heating element size for this type of approach.

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APPENDIX A: Energy Plus Engineering Reference

A.1 General Modeling Overview

The EnergyPlus program is a collection of many program modules that work together to calculate the energy required for heating and cooling a building using a variety of systems and energy sources. It does this by simulating the building and associated energy systems when they are exposed to different environmental and operating conditions. The core of the simulation is a model of the building that is based on fundamental heat balance principles.

A.2 Simulation Manager

The simulation manager of EP is contained in a single module. The main subroutine is shown in figure A.1 Flow within the entire program is managed using a series of

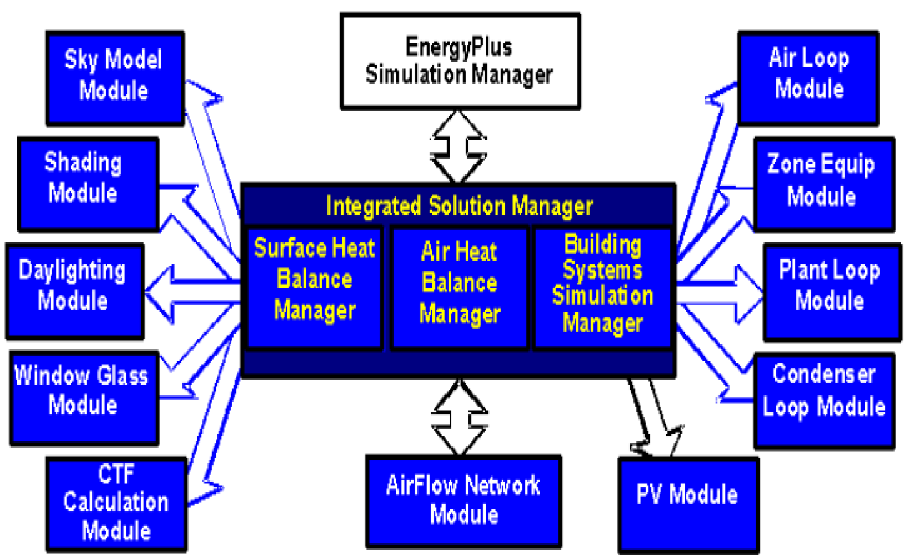

Figure A.1: Energy Plus Program Schematic

flags. These paired flags, in order (from the highest to the lowest) are in table A.1 There is also a WarmupFlag to signal that the program is in warmup state. The operation of these flags can be seen in the following subroutine. This code is actually

Table A.1: Simulation Flags

BeginSimulationFlag	EndSimulationFlag
BeginEnvironmentFlag	EndEnvironmentFlag (one to many days)
BeginDayFlag	EndDayFlag
BeginHourFlag	EndHourFlag
BeginTimeStepFlag	EndTimeStepFlag

simplified, old EnergyPlus FORTRAN code but it concisely demonstrates the use of these flags in the code. The advantage of using the flag system is that any subroutine throughout the code can determine the exact state of the simulation by checking the status of the flags.

A.3 Simulation Models

A.3.1 Water Heater Thermal Tank

Water thermal tanks are devices for storing thermal energy in water. The most common types are water heaters. devices for storing and heating water. Typical water heater applications are for domestic hot water heating, low-temperature radiant space heating, and energy storage for solar hot water systems or waste heat recovery. In EnergyPlus, water heater objects can be coupled to a plant loop simulation or used stand-alone. There are also chilled water storage tanks that can be used to hold cold water.

A.3.1.1 Mixed Water Thermal Tank

The input object WaterHeater:Mixed provides a model that simulates a well-mixed water tank, i.e. non-stratified, and is appropriate for simulating many types of water heaters and storage tanks, including gas and electric residential water heaters, a variety of large commercial water heaters, and also instantaneous, tankless water heaters. This model is used for both the mixed water heater and the mixed chilled water storage tanks.

A.3.1.1.1 Energy Balance

The well-mixed assumption implies that all water in the tank is at the same temperature. To calculate the water temperature, the model analytically solves the differential equation governing the energy balance of the water tank:

$$\rho V C_p \frac{dT}{dt} = q_{net} \tag{A.1}$$

where: ρ is the density of water, V is the volume of the tank, C_p is the specific heat of water, T is the temperature of the tank water, t is the time, q_{net} is the heat transfer rate to the tank water The density and volume can be replaced with the total mass m of water in the tank to get:

$$m C_p \frac{dT}{dt} = q_{net} \tag{A.2}$$

The net heat transfer rate q_{net} is the sum of gains and losses due to multiple heat transfer pathways.

$$q_{net} = q_{heater} + q_{oncycpara} + q_{offcycpara} + q_{oncycloss} + q_{offcycloss} + q_{use} + q_{source} \tag{A.3}$$

where:

q_{heater} is the heat added by the heating element or burner.

$q_{oncycpara}$ is the heat added due to on-cycle parasitic loads (zero when off)

$q_{offcycpara}$ is the heat added due to off-cycle parasitic loads (zero when on)

$q_{oncycloss}$ is the heat transfer to/from the ambient environment (zero when off)

$q_{offcycloss}$ is the heat transfer to/from the ambient environment (zero when on)

q_{use} is the heat transfer to/from the use side plant connections

q_{source} is the heat transfer to/from the source side plant connections

$q_{oncycloss}$ & $q_{offcycloss}$ are defined as

$$q_{\text{oncycloss}} = UA_{\text{oncyc}} \left(T_{\text{amb}} - T\right) \tag{A.4}$$

$$q_{\text{offcycloss}} = UA_{\text{offcyc}} \left(T_{amb} - T\right) \tag{A.5}$$

where:

UA_{oncyc} is the on cycle loss coefficient to ambient environment (zero when off)

UA_{offcyc} is the off cycle loss coefficient to ambient environment (zero when on)

T_{amb} is the temperature of ambient environment

q_{use} & q_{source} are defined as:

$$q_{use} = \varepsilon_{use} \dot{m}_{use} c_p \left(T_{use} - T\right) \tag{A.6}$$

$$q_{source} = \varepsilon_{\text{source}} \, \dot{m}_{\text{source}} \, c_p \left(T_{\text{source}} - T\right) \tag{A.7}$$

where:

$\varepsilon_{\text{source}}$ is the heat exchanger effectiveness for the use side plant connections

$\dot{m}_{use}$ is the mass flow rate for the use side plant connections

$\dot{m}_{\text{source}}$ is the inlet fluid temperature of the use side plant connections

$\varepsilon_{\text{source}}$ is the heat exchanger effectiveness for the source side plant connections

$\dot{m}_{\text{source}}$ is the mass flow rate for the source side plant connections

T_{source} is the inlet fluid temperature of the use side plant connections.

Incorporating all of these equations into the original differential equation:

$$\begin{aligned} mC_p \frac{dT}{dt} = & q_{\text{heater}} + q_{\text{oncyc}} + q_{\text{offcyc}} + UA_{\text{oncyc}} \left(T_{\text{amb}} - T\right) + UA_{\text{offcyc}} \left(T_{\text{amb}} - T\right) \\ & + \varepsilon_{\text{use}} \, \dot{m}_{\text{use}} \, C_p \left(T_{\text{use}} - T\right) + \varepsilon_{\text{source}} \, \dot{m}_{\text{source}} \, C_p \left(T_{\text{source}} - T\right) \end{aligned} \tag{A.8}$$

Associating terms not dependent on temperature T and terms dependent on temperature T yields:

$$\frac{dT}{dt} = \left[\frac{1}{mC_p}\left(\begin{array}{c} q_{\text{heater}} + q_{\text{oncyc}} + q_{\text{offcyc}} + UA_{\text{oncyc}}\,T_{\text{amb}} + UA_{\text{offcyc}}\,T_{\text{amb}} \\ +\varepsilon_{\text{use}}\,\dot{m}_{\text{use}}\,C_pT_{\text{use}} + \varepsilon_{\text{source}}\,\dot{m}_{\text{source}}\,C_pT_{\text{source}} \end{array}\right)\right] + \left[\frac{-1}{mC_p}\left(UA_{\text{oncyc}} + UA_{\text{offcyc}} + \varepsilon_{\text{use}}\,\dot{m}_{\text{use}}\,C_p + \varepsilon_{\text{source}}\,\dot{m}_{\text{source}}\,C_p\right)\right]T \tag{A.9}$$

The differential equation now has the form:

$$\frac{dT}{dt} = a + bT \tag{A.10}$$

where:

$$a = \frac{1}{mc_p}\left(\begin{array}{c} q_{heater} + q_{oncyc} + UA_{oncyc}T_{amb} + UA_{offcyc}T_{amb} \\ +\varepsilon_{use}\dot{m}_{use}c_pT_{use} + \varepsilon_{source}\dot{m}_{source}c_pT_{source} \end{array}\right) \tag{A.11}$$

$$b = \frac{-1}{mc_p}\left(UA_{oncyc} + UA_{offcyc} + \varepsilon_{use}\dot{m}_{use}c_p + \dot{m}_{source}c_p \right) \tag{A.12}$$

The solution to the differential equation can be written in terms of a and b as:

$$T(t) = \left(\frac{a}{b} + T_i\right)e^{bt} - \frac{a}{b} \tag{A.13}$$

where:

$T(t)$ =temperature of the tank water at time t

T_i = initial temperature of the tank water at time $t = 0$

However, if $b = 0$, the solution instead is:

$$t = \frac{1}{b}ln\left(\frac{\frac{a}{b} + T_f}{\frac{a}{b} + T_i}\right) \tag{A.14}$$

or if $b = 0$:

$$t = \frac{T_f - T_i}{a} \tag{A.15}$$

where T_f is the final temperature of the tank water at time t. In the special case where $b = 0$ and $a = 0$, and $T_f \neq T_i$, the time t is infinity.

A.3.1.1.2 Water Heater Control Algorithm

For water heaters, control options allow the heater to cycle or modulate to meet the load. When cycling, the heater element or burner is either on or off. The heater remains fully on while heating the tank up to the set point temperature. When the set point is reached, the heater turns off. The heater remains off until the tank temperature falls below the "cut-in" temperature, i.e., the set point temperature minus the dead band temperature difference. The heater continuously cycles on and off to maintain the tank temperature within the dead band. Most storage-tank water heaters cycle.

When modulating, the heater power varies between the maximum and minimum heater capacities. The heater stays on as long as the required total demand is above the minimum capacity. Below the minimum capacity, the heater will begin to cycle on and off based on the dead band temperature difference. Most tankless/instantaneous water heaters modulate.

Within a time step, the differential equation is solved separately for when the heater element or burner is "on" (on-cycle) and when it is "off" (off-cycle). This approach allows ambient losses and parasitic loads to be divided into on-cycle and off-cycle effects and accounted for in detail. An illustration (figure A.2) of how the control algorithm cycles on and off is shown below. Ambient losses cool the tank temperature until the bottom of the dead band is reached ($50°C$) at which point the heater cycles on and reheats the tank back to the set point ($60°C$). A water draw causes hot water to be replaced with cold water from the water mains. The incoming cold water rapidly cools the tank. In this example the heater cannot keep up with the water draw and the tank temperature continues to drop until the water draw ends.

Although the instantaneous tank water temperature may vary considerably within

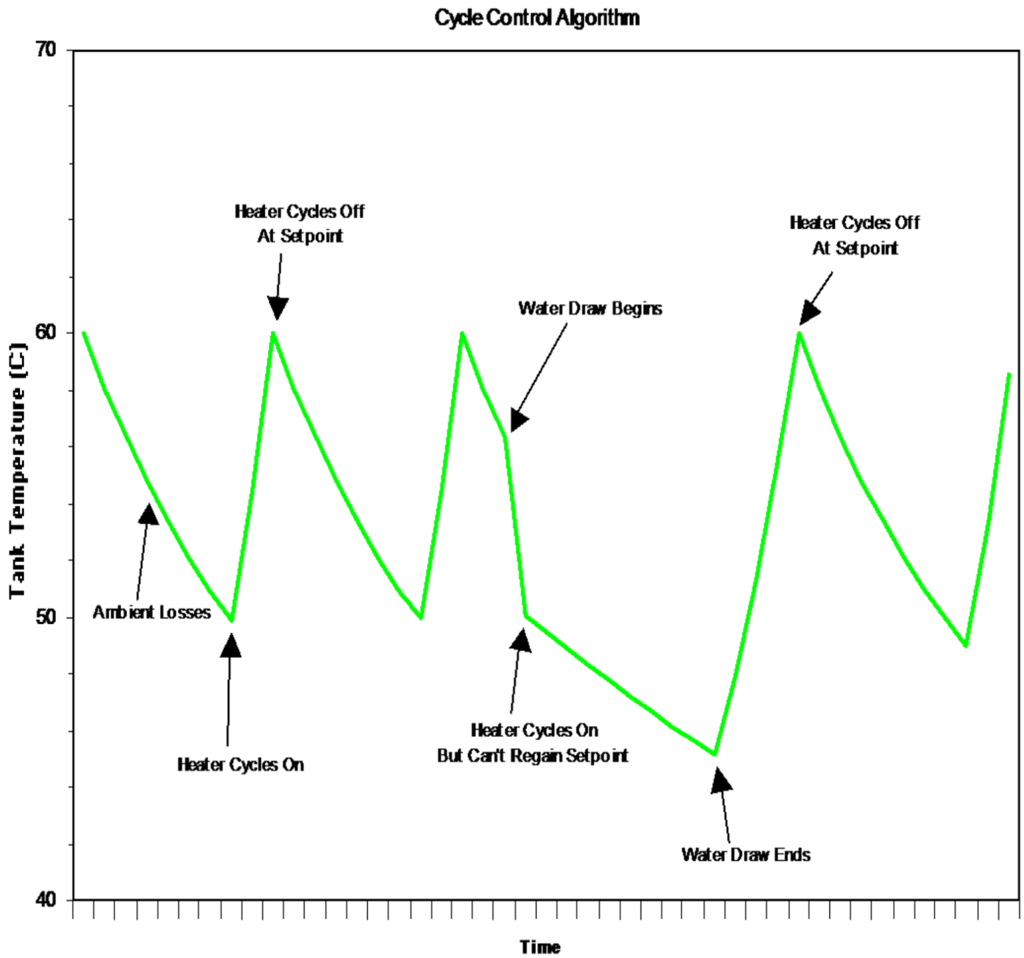

Figure A.2: Water Heater Cycle Control Algorithm

a time step (due to cycling, etc.), only the average temperature over the time step is reported. The model calculates the average by piece-wise integration of the area under the instantaneous temperature curve for each unique set of conditions. The instantaneous temperature is preserved internally by the program and is propagated from the end of one time step to the beginning of the next.

A.3.1.1.3 Standard Ratings

For water heaters, the industry standard ratings of Recovery Efficiency and Energy Factor are calculated according to the [35] test procedure. To emulate the test procedure, a 24-hour simulation of the water heater is performed internally using the specified test conditions:

- Setpoint Temperature = $57.2°C\,(135°F)$
- Ambient Temperature = $19.7°C\,(67.5°F)$
- Ambient Relative Humidity = 50% (used for heat pump water heaters)
- Inlet Temperature (Water Mains) = $14.4°C\,(58°F)$

APPENDIX B: WaterHeater:Mixed

The WaterHeater: Mixed object analytically solves the differential equation governing the energy balance of the water tank. Within a timestep, conditions are solved separately for when the heater element or burner is "on" (on-cycle) and when it is "off" (off-cycle). This approach allows ambient losses and parasitic loads to be divided into on-cycle and off-cycle effects and accounted for in detail.

For losses to the ambient environment, the ambient air temperature can be taken from a schedule, a zone, or the exterior. When used with a zone, a fraction of the skin losses can be added to the zone heat balance as internal heat gains.

Control options allow the heater to cycle or modulate to meet the load. When cycling, the heater element or burner is either on or off. The heater remains fully on while heating the tank up to the setpoint temperature. When the setpoint is reached, the heater turns off. The heater remains off until the tank temperature falls below the "cut-in" temperature, i.e., the setpoint temperature minus the deadband temperature difference. The heater continuously cycles on and off to maintain the tank temperature within the deadband. Most storage-tank water heaters cycle.

When modulating, the heater power varies between the maximum and minimum heater capacities. The heater stays on as long as the required total demand is above the minimum capacity. Below the minimum capacity, the heater will begin to cycle on and off based on the deadband temperature difference. Equipment is usually designed and rated to avoid this condition. Most tankless/instantaneous water heaters modulate.

It has following inputs

- Field: Name

  The name of the WaterHeater: Mixed object.

- Field: Tank Volume

The volume of the storage tank [m3]. This field is autosizable if used with a Water Heater:Sizing object. Although this field is allowed to go down to zero, even so-called "tankless" water heaters have some volume of water that is maintained around the heating elements or in the heat exchanger, typically around $0.00379m^3$ (1 gallon).

- Field: Setpoint Temperature Schedule Name

  The reference to the schedule object specifying the hot water temperature setpoint [$^\circ C$]. Also known as the "cut-out" temperature.

- Field: Deadband Temperature Difference

  The delta temperature difference [$\Delta^\circ C$] between the setpoint and the "cut-in" temperature at which the heater will turn on. In other words, the "cut-in" temperature is Setpoint Deadband.

- Field: Maximum Temperature Limit

  The temperature [$^\circ C$] at which the tank water becomes dangerously hot and is vented through boiling or an automatic safety. The tank temperature will never exceed the maximum. Any extra heat added to the tank is immediately vented. Note: The maximum temperature must be greater than the setpoint temperature at all times.

- Field: Heater Control Type

  The control type can be Cycle or Modulate. Cycle is appropriate for most storage tank-type water heaters. Modulate is appropriate for most instantaneous/tankless water heaters.

- Field: Heater Maximum Capacity

  The maximum heat rate [W] that can be supplied to the water, probably the same as the "nominal" capacity. This field is autosizable if used with a Water

Heater: Sizing object.

- Field: Heater Minimum Capacity

  The minimum heat rate [W] that can be supplied to the water. This field is only used when the Heater Control Type is Modulate. If the total demand rate for heating is less than the minimum, even a modulating water heater will begin to cycle.

- Field: Heater Fuel Type

  The type of fuel used for heating. The fuel type can be Electricity, NaturalGas, Propane, FuelOilNo1, FuelOilNo2, Coal, Diesel, Gasoline, Steam, OtherFuel1, OtherFuel2 or DistrictHeating.

- Field : Heater Thermal Efficiency

  The thermal conversion efficiency from fuel energy to heat energy for the heater element or burner. This is not the same as the overall efficiency of the water heater.

- Field : Part Load Factor Curve Name

  The reference to the curve object that relates the overall efficiency of the water heater to the Runtime Fraction (if Control Type Cycle) or Part Load Ratio (if Control Type Modulate). This is an additional multiplier applied to the Heater Thermal efficiency to compute fuel energy use. The Part Load Factor Curve should not have a value less than 0.1 in the domain from $0 to 1$. If the Part Load Factor Curve accounts for ambient losses and/or parasitic fuel consumption, these effects should not also be input into the related fields in this object as that would result in double-counting.

- Field: Off-Cycle Parasitic Fuel Consumption Rate

  Off-cycle parasitics include parts of the water heater that consume fuel when the heater is off, for example, a pilot light, or stand-by electronic control circuits. The fuel consumption rate [W] is strictly the total fuel that is consumed by all of the off-cycle parasitics.

- Field: Off-Cycle Parasitic Fuel Type

  The type of fuel used by the off-cycle parasitics. The fuel type can be Electricity, NaturalGas, Propane, FuelOilNo1, FuelOilNo2, Coal, Diesel, Gasoline, Steam, OtherFuel1, OtherFuel2 or DistrictHeating. The fuel type can be the same or different from the Heater Fuel Type.

- Field: Off-Cycle Parasitic Heat Fraction to Tank

  The fraction of off-cycle parasitic fuel energy that is converted to heat energy that ends up in the tank water. For example, a pilot light would deliver most of its heat to the tank water, as long as the thermal conversion efficiency must be taken into account, so perhaps 0.80 is reasonable. Electronic control circuits, on the other hand, do not add any heat to the tank and should be 0.

- Field: On-Cycle Parasitic Fuel Consumption Rate

  On-cycle parasitics include parts of the water heater that consume fuel when the heater is on, for example, an induction fan, or stand-by electronic control circuits. The fuel consumption rate [W] is strictly the total fuel that is consumed by all of the on-cycle parasitics.

- Field: On-Cycle Parasitic Fuel Type

  The type of fuel used by the on-cycle parasitics. The fuel type can be Electricity, NaturalGas, Propane, FuelOilNo1, FuelOilNo2, Coal, Diesel, Gasoline, Steam, OtherFuel1, OtherFuel2 or DistrictHeating. The fuel type can be the same or different from the Heater Fuel Type.

- Field: On-Cycle Parasitic Heat Fraction to Tank

The fraction of on-cycle parasitic fuel energy that is converted to heat energy that ends up in the tank water. For example, an induction fan might (maybe) deliver a small fraction of its energy to the tank water for a value of 0.05. Electronic control circuits, on the other hand, do not add any heat to the tank and should be 0.

- Field: Ambient Temperature Indicator

  The Ambient Temperature Indicator specifies how the ambient air temperature will be indicated. The field can be Schedule, Zone, or Outdoors. If Schedule is used, the Ambient Temperature Schedule field provides the ambient temperature. If Zone is used, the zone air temperature of the zone specified in the Ambient Temperature Zone field provides the ambient temperature. If Outdoors is used, the outdoor dry-bulb air temperature provides the ambient temperature.

- Field: Ambient Temperature Schedule Name

  he reference to the schedule object specifying the ambient air temperature around the tank for skin losses. This field is only used if Ambient Temperature Indicator is Schedule.

- Field: Ambient Temperature Zone Name

  The reference to the zone object specifying the ambient air temperature around the tank for skin losses. This field is only used if Ambient Temperature Indicator is Zone.

- Field: Ambient Temperature Outdoor Air Node Name

  This optional alpha field specifies the outdoor air node name used to define the ambient conditions surrounding the water heater tank. This field is applicable only when the Ambient Temperature Indicator is specified as Outdoors, otherwise this field should be left blank. The node name specified must also be specified in an OutdoorAir : Node object where the height of the node is taken into consideration when calculating outdoor air conditions from the weather data. Alternately, the node name may be specified in an OutdoorAir : NodeList object where the outdoor air conditions are taken directly from the weather data.

- Field: Off-Cycle Loss Coefficient to Ambient Temperature

  The loss coefficient [W/K] to the ambient air temperature. Often this coefficient is identical to the "UA" for skin losses. However, it can also be used to model the loss effects of the flue in a combustion water heater, in addition to the skin losses.

- Field: Off-Cycle Loss Fraction to Zone

  If the Ambient Temperature Indicator is Zone, this field adds the specified fraction of the off-cycle losses to the zone heat balance as an internal gain.

- Field: On-Cycle Loss Coefficient to Ambient Temperature

  The loss coefficient [W/K] to the ambient air temperature. Often this coefficient is identical to the "UA" for skin losses. If the loss effects of the flue are being modeled in the Off-Cycle Loss Coefficient, than this field would have a different value accounting only for the skin losses.

- Field: On-Cycle Loss Fraction to Zone

  If the Ambient Temperature Indicator is Zone, this field adds the specified fraction of the on-cycle losses to the zone heat balance as an internal gain.

- Field: Peak Use Flow Rate

  The peak flow rate $[m^3/s]$ of domestic hot water usage for stand-alone operation, i.e., without plant loop node connections. The peak value is multiplied by the Use Flow Rate Fraction Schedule. If there are node connections, this field is not used.

- Field: Use Flow Rate Fraction Schedule Name

  The reference to the schedule object specifiying the current fraction of Peak Volumetric Use Flow Rate of domestic hot water usage for stand-alone operation.

- Field: Cold Water Supply Temperature Schedule Name

  The reference to the schedule object specifying the cold water temperature [$°C$] from the supply mains that makes up for the hot water lost down the drain. If blank, water temperatures are calculated by the Site: WaterMainsTemperature object. This field is for stand-alone operation only. If there are node connections, this field is not used.

- Field: Use Side Inlet Node Name

  The inlet node connection to the plant loop for the use side of the water heater. Typically the use side draws hot water from the tank and returns cooler water.

- Field: Use Side Outlet Node Name

  The outlet node connection to the plant loop for the use side of the water heater. Typically the use side draws hot water from the tank and returns cooler water.

- Field: Use Side Effectiveness

  This field specifies the heat transfer effectiveness between the use side water and the tank water. If the effectiveness is set to 1 then complete heat transfer occurs, simulating perfect mixing of the use side water and the tank water. If the effectiveness is lower, then the use side outlet water temperature will not be as hot as the tank water, simulating a heat exchanger.

- Field: Source Side Inlet Node Name

  The inlet node connection to the plant loop for the source side of the water heater. Typically the source side draws cold water from the tank and returns warmer water. The source side volume flow rate is obtained from the plant loop. The magnitude of the flow rates through the source side can be controlled by setting the Maximum Branch Flow Rate field in the Branch object that connects the source inlet node.

- Field: Source Side Outlet Node Name

  The outlet node connection to the plant loop for the source side of the water heater. Typically the source side draws cold water from the tank and returns warmer water.

- Field: Source Side Effectiveness

  This field specifies the heat transfer effectiveness between the source side water and the tank water. If the effectiveness is set to 1 then complete heat transfer occurs, simulating perfect mixing of the source side water and the tank water. If the effectiveness is lower, then the source side outlet water temperature will not be as hot as the tank water, simulating a heat exchanger.

- Field: Use Side Design Flow Rate

  This field is optional and is used to specify the design flow rate through the Use Side of the water heater. The volumetric design flow rate is specified in m^3/s. The field is needed when the Use Side is connected to a plant loop. The field can be autosized. If autosized, then the input file should include a Plant Sizing object for the plant loop. Sizing results are reported in the EIO file.

- Field: Source Side Design Flow Rate

  This field is optional and is used to specify the design flow rate through the Source Side of the water heater. The volumetric design flow rate is specified in m^3/s. The field is needed when the Source Side is connected to a plant loop. The field can be autosized. If autosized, then the input file should include a

Plant Sizing object for the plant loop. Sizing results are reported in the EIO file.

- Field: Indirect Water Heating Recovery Time

  This field is optional and is used to provide a design parameter for autosizing design flow rates when the waterheater is connected to the demand side of a plant loop. The recovery time is expressed in hours. This is the time that the entire volume of the tank can be heated from $14.4°C\,to\,57.2°C(58°Fto135°F)$ with an inlet temperature defined as the exit temperature in the associated Plant Sizing object. The default is 1.5 hours. The calculation is based on log-mean temperature difference (LMTD) and includes the heat transfer effectiveness factor entered above.

- Field: Source Side Flow Control Mode

  This field is optional and is used to provide control over the logic used by the source side of the water heater to request flow. There are three choices for different modes: IndirectHeatPrimarySetpoint, IndirectHeatAlternateSetpoint, or StorageTank. The mode called IndirectHeatPrimarySetpoint is the historical behavior prior to version 8.1. In this mode the water heater will request flow at the source side when the main setpoint, in the input field called Setpoint Temperature Schedule Name, and deadband call for the tank to be heated. This mode is typical for a water heater indirectly heated by a boiler. The mode called IndirectHeatAlternateSetpoint is similar but it bases its control decisions on an alternate setpoint given in the following field. This mode is useful when the indirect source of heat may not satisfy the load and an internal heater is used for backup. The mode called StorageTank is for a passive tank and it always requests flow unless the tank temperature is equal to or higher than the maximum limit given in the input field called Maximum Temperature Limit.

- Field: Indirect Alternate Setpoint Temperature Schedule Name

  his field is optional and is used to provide a schedule with alternate setpoints for use with the IndirectHeatAlternateSetpoint mode in the previous field. The input field should contain a reference to a schedule object specifying the hot water temperature setpoint [$°C$] to use as the "cut-out" temperature for control logic at the source side.

- Field: End-Use Subcategory

  This optional field allows you to specify a user-defined end-use subcategory, e.g., "Process". A new meter for reporting is created for each unique subcategory (ref: Output:Meter objects). Any text may be used here to further subcategorize the end-uses in the ABUPS End Uses by Subcategory table and in the LEED Summary EAp2-4/5 Performance Rating Method Compliance table. If this field is omitted or blank, the water heater will be assigned to the "General" end-use subcategory.

APPENDIX C: Domestic Hot Water

The mains water temperature for a typical house varies significantly depending on the location and time of year. The following equation, based on TMY2 data for the location of the Prototype, shall be used to determine the daily mains water temperature for both the Benchmark and the Prototype:

$$\begin{aligned} T_{mains} = (T_{amb,avg} + offset) + ratio * (\Delta)T_{amb,max}/2) \\ *sin(0.986 * (day\# - 15 - lag) - 90) \end{aligned} \tag{C.1}$$

where: T_{mains} = mains (supply) temperature to domestic hot-water tank ($^{\circ}F$)

$T_{amb,avg}$ = annual average ambient air temperature ($^{\circ}F$)

$\Delta T_{amb,max}$ = maximum difference between monthly average ambient temperatures (e.g., $T_{amb,avg,july} - T_{amb,avg,january}(^{\circ}F)$)

0.986 = degrees/day (360/365)

day# = Julian day of the year (1-365)

offset = $6^{\circ}F$

ratio = $0.4 + 0.01(T_{amb,avg} - 44)$

lag = $35 - 1.0(T_{amb,avg} - 44)$

This equation is based on analysis by Christensen and Burch of NREL using data for multiple locations, as compiled by Abrams and Shedd [36], Florida Solar Energy Center [37], and Sandia National Laboratories [38]. The offset, ratio, and lag factors were determined by fitting the available data. The climate-specific ratio and lag factors are consistent with water pipes being buried deeper in colder climates. The offset, ratio, and lag factors were determined by fitting the available data. The climate-specific ratio and lag factors are consistent with water pipes being buried deeper in colder climates.

In order for the constant terms in the ratio and lag factors to be representative of

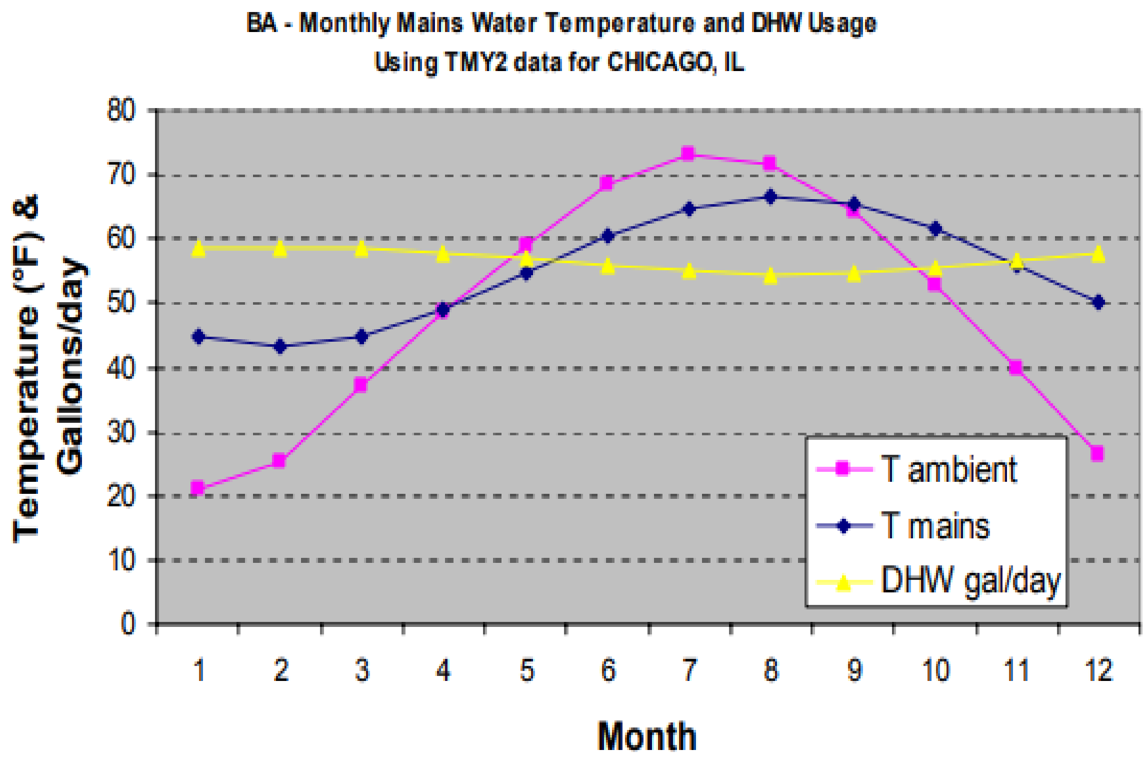

Figure C.1: Mains temperature profile for Chicago [6] published in 2006

an average climate, the data fitting was done relative to a nominal $T_{amb,avg} = 44°F$. The lag is relative to ambient air temperature, and $T_{amb,minimum}$ is assumed to occur in midJanuary (day$\#$ = 15). The choices for these nominal values are not critical, because although different assumptions would change the constant terms in the ratio and lag factors, the coefficients would also change, so the prediction of T_{mains} values would be unchanged. For models that use average monthly mains temperature, $day\#$ in equation C.1 shall be calculated using

$$day\# = 30 * month\# - 15 \qquad \text{(C.2)}$$

where: month$\#$ = month of the year (1-12)

An example using C.1, C.2 to determine the monthly mains temperature profile for Chicago, Illinois is shown in figure C.1