# Optimization of Thermal Energy Storage Sizing Using Thermodynamic Analysis

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# OPTIMIZATION OF THERMAL ENERGY STORAGE SIZING USING THERMODYNAMIC ANALYSIS

A Thesis Presented

By

Andrew M. Villanueva

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Mechanical and Industrial Engineering

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# ABSTRACT

## OPTIMIZATION OF THERMAL ENERGY STORAGE SIZING USING THERMODYNAMIC ANALYSIS

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The aim of this thesis is to examine the effect that Thermal Energy Storage (TES) sizing has on a building's ability to meet heating and cooling demands in an energy and cost efficient manner. The focus of the research is the quantification the effects of TES for system sizing and boiler cycling. Research is accomplished by modelling TES systems with various storage capacities using thermodynamic analysis.

Energy costs are subject to increase during peak usage periods due to a limited supply of energy. Peak heating and cooling periods also force thermal systems to be sized for loads that are only experienced for a small fraction of the year leading to poor efficiencies and frequent cycling during off peak times of year. TES introduces the capability to mitigate this issue by shifting peak thermal loads from one period to another, theoretically reducing the minimum necessary boiler or chiller capacity for a given system and potentially improving the efficiency of thermal systems. The scope of this research is to model the operation of thermal systems with varying storage capacities in order to quantify these capabilities with respect to capacity and cycling. This is accomplished with modelling in *Transient Systems Simulation Program* (TRNSYS). In this software, a simple heating loop and cooling loop are independently considered and subjected to hourly load data extrapolated from heating and cooling load data originating from a retirement community in Massachusetts. The model built is intended to be robust enough to be easily applied and adapted to assess similar problems with energy storage capacity sizing.

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# CHAPTER 1

# INTRODUCTION

## 1.1 Background Information

According to data collected and analyzed by the U.S. Energy Information Administration, heating and cooling represents an appreciable fraction of energy consumption in the manufacturing, commercial and residential sectors. For example, according to a Manufacturing Energy Consumption Survey (MECS) conducted in 2014, of the 14.9 quadrillion BTUs of fuel used in the American manufacturing sector, 24% of total fuel consumption was used for heating purposes, and 17% of total fuel consumption was used for cooling and facility HVAC (MECS 5.1)[1]. Similarly, data collected in 2009 states that 6 quadrillion BTUs, or 59% of energy consumption in the American residential sector was attributed to heating needs (CE3.1)[2]. In 2012, 25% or about 1,700 million MMBtus of energy usage in commercial buildings was attributed to space heating alone (CBECS E1)[3]. The ubiquity of heating and cooling systems across all sectors makes them a prime target for developments with respect to energy efficiency. One such technology that has garnered a great deal of interest is Thermal Energy Storage (TES).

While the manner in which TES systems operate varies with respect to time-scale of storage, system size, and storage medium, all TES systems operate on the principle of storing energy for later use [4]. In doing so, TES gives buildings the ability to size and operate heating and cooling systems more optimally, meanwhile ensuring the systems' proficiency at meeting peak heating and cooling demands. The employment of TES allows peak loads to be shifted from one period to another by heating or cooling in excess of the load during off peak hours (charging),and storing the excess for use during peak hours (discharging).

## 1.2 Potential Benefits of TES

### 1.2.1 Demand Side Management

TES represents a widely accessible way to introduce Demand Side Management (DSM) to a system. DSM can reduce energy costs of a thermal system by limiting peak demands and shaping loads based on energy price fluctuations [5]. In order to incentivize peak demand reduction by the end user, facilities are often charged based on their highest monthly peak demand by energy distributors. The cost of energy for end users can also vary throughout the day or year based on fluctuations in fuel supply and demand. By encouraging users to shift energy usage away from off-peak periods, utilities are able to postpone the need for additional generation capacity and instead make better use of base load plants.

For example, in simulating the application of TES in Miami, Lisbon, Shanghai, and Mumbai, Deforest et al. [6] found that TES has the potential to reduce annual electricity costs by 5-15%, and peak electricity consumption by 13-33% based on the electricity rates/tariffs and climates, respective to each location. Z. Zhang et al. [5] assessed the cost and energy savings associated with implementing a shared TES tank for four chiller plants in Austin, Texas using a self-built system model and a direct search method for optimizing chiller operation. Each chiller plant has a capacity of 5,450 tons, 4,570 tons, 1,180 tons, and 1,600 tons for a total of 12,800 tons of combined cooling capacity supplied by 13 chillers with estimated efficiencies ranging from 0.6 to 0.9 kW per ton. Based on the electricity rate structures, energy usage, and performance characteristics of the chillers, a baseline cooling load was estimated and an optimal control strategy for each month was determined. The resulting annual cost savings were used to identify the optimal storage volume out of eight options ranging from 1.0 to 7.0 million gallons with respect to simple payback. The optimal storage size was determined to be 3.5 million gallons as demand savings tended towards a constant value at larger volumes. The results of the model indicated that over 70% of annual cost savings would be from the decrease in demand charges. A sensitivity analysis of the model lead to the conclusion that the simple payback of the project is most heavily affected by the chiller plants' load factor; a reduction of the load factor from 1.08 to 0.84 allows the less efficient chillers to be used less frequently, reducing the simple payback period of the project by 25%

### 1.2.2 Thermal System Sizing

In addition to the reduction of peak demand, TES has the potential to decrease energy consumption by increasing the operating efficiency of a boiler or chiller. Boilers and chillers typically perform optimally when operating close to their design capacities, and performance decreases at lower Part Load Ratios (PLR)[7].

Thermal energy systems are often oversized in order to ensure their ability to deliver the necessary heating or cooling during the hottest or coldest times of the year, often increasing their initial installation costs, energy and maintenance costs by forcing the equipment to run inefficiently. This is a persistent problem across systems of all sizes and applications.

With respect to the manufacturing sector where heating and cooling is essential to daily operations, reliability of such systems is highly critical. In order to ensure that thermal needs are met during worst-case scenarios, designers are prone to specifying equipment that is oversized for nominal plant operation. It is not uncommon for facilities to have multiple boilers, each rated at several times the maximum expected load [8]. Although this is often a consequence of efforts to improve reliability, the result is commonly less reliability because of additional wear on equipment and low-efficiency operation [9].

Peeters et al. [10] assessed the effect of boiler sizing in residential buildings on energy consumption and occupancy comfort with respect to a modulating condensing boiler, and a non-modulating high efficiency boiler through the use of numerical modelling. They found that in both boilers, gas consumption increased with boiler output capacity when subjected to the same loading conditions. This increase was more evident in the non-modulating high efficiency boiler due to greater boiler cycling and boiler skin losses with larger boiler capacities. The modulating condensing boiler also exhibited a decrease in efficiency with increasing capacity. Overall, the study found that the overall efficiency of the modulating condensing boiler dropped from 88% to 80% over the increase of boiler capacity of 13.6 kBtu to 27.2 kBtu. Similarly, the non-modulating high efficiency boiler overall efficiency dropped from 72% to 53% over the same range.

In the case of cooling, an oversized chiller will result in an increase in hours that the chiller runs at reduced loads. This is problematic because chiller efficiency tends to drop off rapidly with smaller part load ratios. In analyzing part load ratio characteristics of chillers in an office building, Seo [7] found that 70% of annual electric consumption lies in the PLR range of 0% to 50%. As such, peak demand management and proper chiller sizing is proven to be critical in the minimization of electricity consumption.

Similar to TES in boiler systems, implementation of TES in chiller systems can allow equipment to be sized more optimally by effectively redistributing peak loads to off peak periods. This mechanism permits the chiller to run at its full capacity and highest efficiency for longer times, thusly decreasing annual energy usage of the chiller, and introducing the ability to select a chiller with a smaller capacity during the system's design.

### 1.2.3 Emissions Reduction

The oversizing of thermal energy systems introduces the potential to drastically increase a greenhouse system's emissions. Although modern boilers are capable of operating continuously at about 30-50% of their nominal load, they are typically forced to cycle if the load demand decreases any further than this minimum. This type of start-stop operating results in an increased number of emission peaks throughout boiler operation. Biomass boilers for residential applications are of particular interest in this respect due to their growing popularity in North America, Europe and Asia, and the large quantity of emissions associated with start and stop cycles. During realistic operation, laboratory measurements of wood pellet boilers have indicated that the majority of annual total organic carbon (TOC) emissions and approximately 30% of particle emissions are produced in the transient phases in wood pellet boiler operation [11]. According to a national research project conducted in Austria, the amount of additional emissions resulting from start-stop operation is directly related to the number of cycles of the boiler [12]. Figure 1 illustrates the evolution of emissions of a biomass boiler during a start-stop cycle.

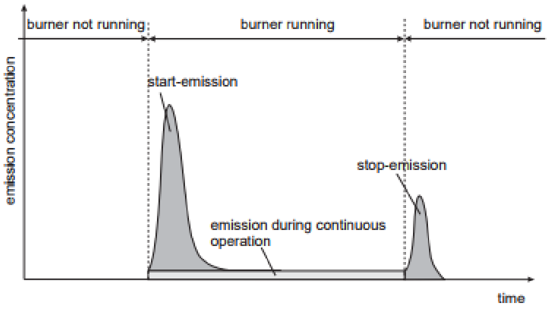


**Figure 1.1: Qualitative Emissions of a Biomass Boiler Cycle [12]**

Laboratory measurements indicate that most of the CO and fine particle (PM2.5) emissions from biomass boilers arise from start-up and stop operation, as evidenced by the following figure.

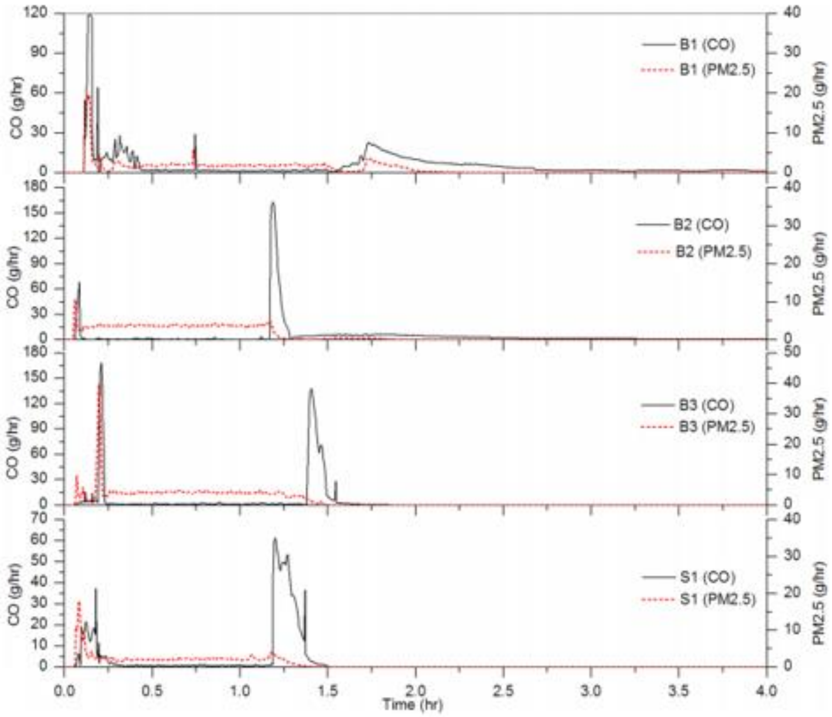


**Figure 1.2: Start and Stop CO and Particle Emission Profiles of Pellet Boilers [7]**

Increased emissions during boiler cycling are a result of the incomplete combustion of the fuel as the flame propagates during the boiler start phase. Additionally, decreased boiler efficiency occurs during cycling because fixed losses such as radiation and skin losses are magnified under lightly loaded conditions in relation to a boiler's useful heat output.

Similar behavior with respect to efficiency and emissions can be seen in natural gas boilers. Cerhuschi et al [13] examined emissions of domestic natural gas boilers using various operating regimes. The study found that a modulating boiler produced more CO emissions than a boiler under on/off operation during intermittent variable, and full constant loads.

TES can also indirectly reduce energy usage, and subsequently emissions, when used in tandem with alternative methods of energy production. Schreiber et al. [14] was able to reduce the primary energy consumption of an industrial process by up to 25% by satisfying discontinuous heat demands of batch processes with stored heat from continuously operated cogeneration units. By the same respect, renewable energy sources that produce energy intermittently, such as solar or wind, have been proven to be more practical with the use of TES. In reviewing state-of-the-art Concentrated Solar Power (CSP) plants around the world, Pelay et al. [15] found that more than 70% of new CSPs required TES systems; most of which being sensible heat storage.

For these reasons, TES has become an increasingly attractive accessory to heating and cooling systems and continues to be a subject of interest in the research and development in energy efficiency. One facet of TES that is in need of studying is the determination of the optimal sizing of TES tanks with respect to heating and cooling loads, and chiller and boiler capacities.

## 1.3 Literature Review

Amini [16] conducted an experimental study of the use of heat pipe technology in thermal energy storage heat exchangers. In this study, Amini examines the effectiveness of Phase Change Material (PCM) as a TES medium. The study focuses on the improvement of the PCM’s ability to charge and discharge quickly. Amini addresses this issue by using heat pipe technology to improve the conductivity between the PCM and the heat transfer fluid (water). In creating an experimental setup consisting of a storage tank, PCM and a finned, multi-legged heat pipe, the feasibility of PCM as a thermal storage medium is demonstrated.

Comodi [17] assesses the feasibility of Cold Thermal Energy Storage (CTES) for building DSM applications in hot climates through the investigation of an office building in Singapore. In the case study, the CTES is combined with the existing cooling systems in order to improve overall efficiency, and to offset energy usage to off-peak periods. In the study, six different CTES sizes are investigated with respect to different percentages of daily cooling energy demands and a total of 465 tons of cooling (1,637 kW). Comodi finds that economic and energy savings can be realized with CTES with a payback ranging from 8.9 to 16 years, meanwhile noting the space necessary for such systems. The shortest payback period of 8.9 years was associated with 127,331 gallons (482 $m^3$) of storage, capable of storing 21.7% of the daily demand.

Rahman [18] constructed a numerical model of a stratified thermal storage tank capable of being applied in building and distributed generation simulations using COMSOL 3-12. The stratified storage tank model does not have mass flow in or out of the tank model. Instead, energy transfer is completed through the use of a heat exchanger. Their model exhibited a phase lag between average tank temperature and stored water temperature of about 9 minutes. Additionally, they found that the heat exchanger flow rate is proportional to the inlet tank temperature. The results of the model agreed with 1-D buoyancy and transient heat source storage models

Haller [19] developed a model of a boiler in TRNSYS, a transient systems simulation software primarily used to model the behavior of dynamic energy systems over long periods in order to estimate energy and cost savings. Once the model was developed, Haller compared it with an investigation of seven boilers. The model was constructed with the objectives of properly modeling flue gas temperature and ambient losses, the efficiency of the condenser, and the cooling of the thermal mass of the boiler. Boiler cycling was also examined. The investigation found that the simulated boiler cycles 25% more than the physical boilers. The difference in cycling was fixed by accounting for the thermal capacitance using measured values. The efficiency of the boiler compared favorably with the boilers investigated with the exception for the delay occurring between lighting of the flame, and the heat transfer to the fluid. Haller concludes that models for this application perform more accurately when unknown parameters are fitted to measurements. A phase lag of 30 minutes between boiler outlet temperature and the energy transfer rate to the fluid pass through the inlet of the boiler. Measured boilers exhibited a two hour phase lag between the two parameters.

Hsieh [20] studied a solar thermal system and compared it with solar thermal systems with various forms of integrated thermal storage from the building to neighborhood scale. The storage was sized such that there was 15.5 $ft^3$ per $ft^2$ (4.7 $m^3$ per $m^2$) of solar collector. In focusing on the fraction of building heat load supplied by solar, the system efficiency of a solar thermal system with integrated storage tank, and the levelized cost of electricity, Hsieh found that storage decreased emissions and increased performance for the system.

## 1.4 Previous Work

In a System Simulation Report for the International Energy Agency, Andreas Heinz studied the use of TES to reduce boiler cycling rates in TRNSYS. In the report, Heinz uses a simple building model in order to allow the thermal interaction between the residential building and the heating system. The building model takes heating loads and the estimated thermal capacity of the building in order to calculate temperatures. In the report simulations, a radiator is used to maintain the room temperature of the building at a constant temperature. A domestic hot water (DHW) profile was also generated. The heat from the radiator and heat required to satisfy DHW needs are used to determine the effective necessary heat output of the boiler at any timestep. Heinz stated that boiler cycling is most dependent on the following boiler characteristics:

Power control of the boilers (on/off or continuously modulating)

Minimum continuous load of the boiler

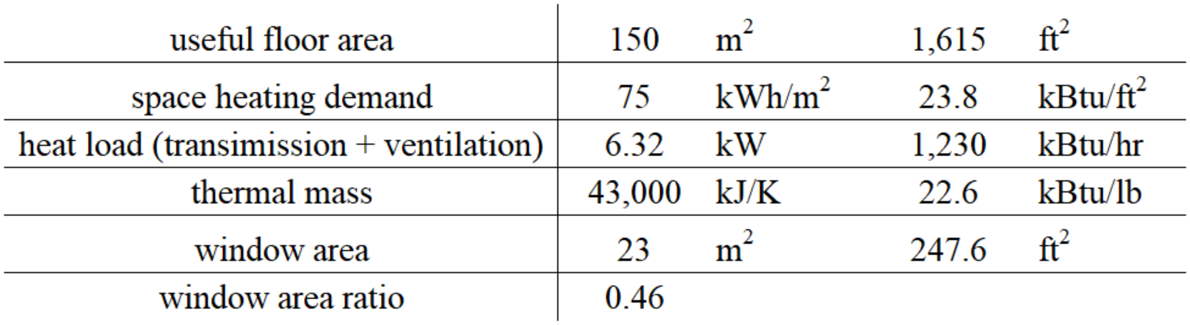
Thermal capacitance of the boiler

Shut off temperature of the boiler

Minimum run time of the boiler

The study varies these characteristics in TRNSYS models using wood pellet boilers and condensing boilers with different hydronic systems, including hydronic systems with TES of up to 500 liters (132 gallons). Heinz found that the addition of storage proved to be most effective at reducing cycling in systems with boilers with low water contents (small thermal mass). In such systems, cycling is able to be reduced to about 20% assuming the addition of 50 liters (13.2 gallons) of storage, a boiler capacity of 12 kW (2,457 kBtu/h) and the following building model parameters

**Table 1.1: Energy model characteristics [Heinz]**



| | | | | |
|---|---|---|---|---|
| useful floor area | 150 | $m^2$ | 1,615 | $ft^2$ |
| space heating demand | 75 | $kWh/m^2$ | 23.8 | $kBtu/ft^2$ |
| heat load (transimission + ventilation) | 6.32 | kW | 1,230 | kBtu/hr |
| thermal mass | 43,000 | kJ/K | 22.6 | kBtu/lb |
| window area | 23 | $m^2$ | 247.6 | $ft^2$ |
| window area ratio | 0.46 | | | |

## 1.5 Scope of Research

The scope of this research is to construct a model that will measure the effect of TES on heating and cooling systems as a whole. Both the heating and cooling model will exhibit the ability for TES to meet heating and cooling loads in a more flexible manner by allowing for the system to store thermal energy proportional to the volume of storage. The heating and cooling systems will be examined independently for different parameters at varying storage capacities. The heating model will focus on the effect of TES with respect to boiler cycling, and the possibility of reducing boiler capacity with the addition of TES. The cooling model will be used to study the possibility of reducing chiller capacity with the addition of TES along with the ability of varying TES capacities to shift on peak loads to off peak periods. The objective of the heating and cooling models will be to aid in the design of thermal systems and to provide a preliminary examination of TES feasibility for systems from the perspective of minimizing capital costs, energy costs and emissions. In order to maintain the adaptability and flexibility of the models, energy balance will be emphasized as opposed to details associated with any given TES heating or cooling system.

# CHAPTER 2

# SIMULATION METHODOLOGY

## 2.1 TES Modeling and Design Tool

The simulated models were created in TRNSYS to model the performance of the heating and cooling system. Both the heating and cooling model share all of the same components with the heating model using a boiler (Type751), and the cooling model using a chiller (Type666).  Figure 2.1 and 2.2 illustrate the basic construction of the models with implemented storage.

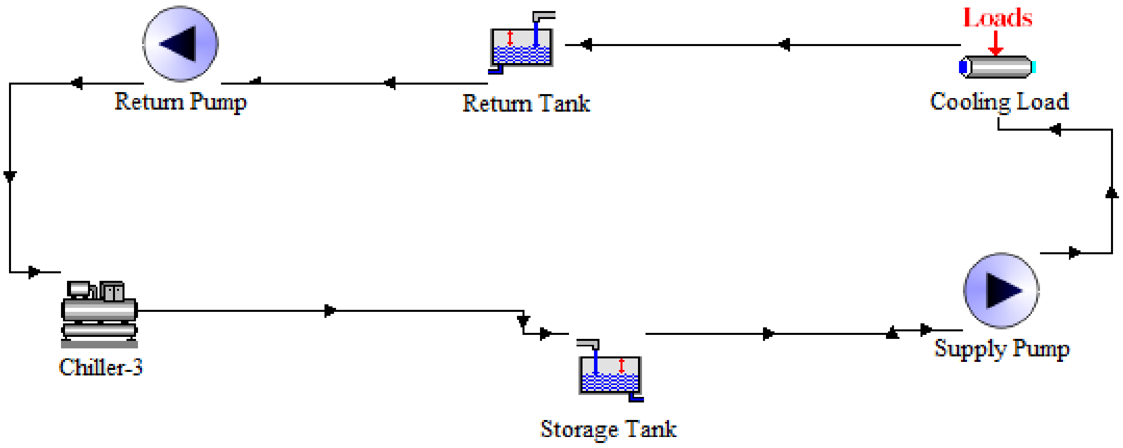


**Figure 2.1**: **TRNSYS chilled water storage model diagram**

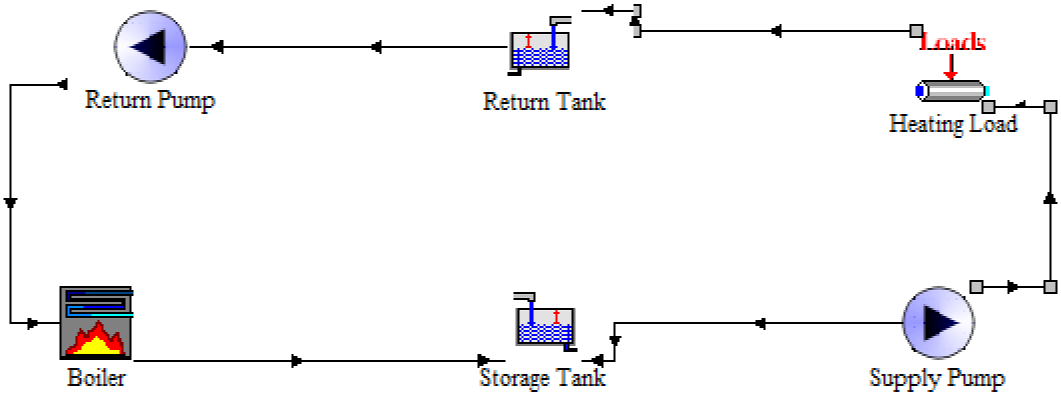


Figure 2.2: TRNSYS hot water storage model diagram

The boiler and chiller in each model are initially sized to meet the annual peak loads (674 kBtuh and 277 tons, respectively) with zero storage volume. To import hourly load data to the TRNSYS models, a data reader component (Type9) was utilized. The data read from this component is connected to the input of the load (Type682), which imposes the load on a flow stream. The flow rate to the load from the constant temperature storage tank (Type32) is controlled in order to maintain a 10 $^{o}$F (5.6 K) temperature difference in the final heating and cooling models. After passing through the load, return water is sent to a return tank which feeds the boiler or chiller with water that is to be sent to storage. The supply and return tank remain at constant temperatures with a 10 $^{o}$F (5.6 K) temperature difference as long as the systems have enough available capacity to satisfy the inputted load.

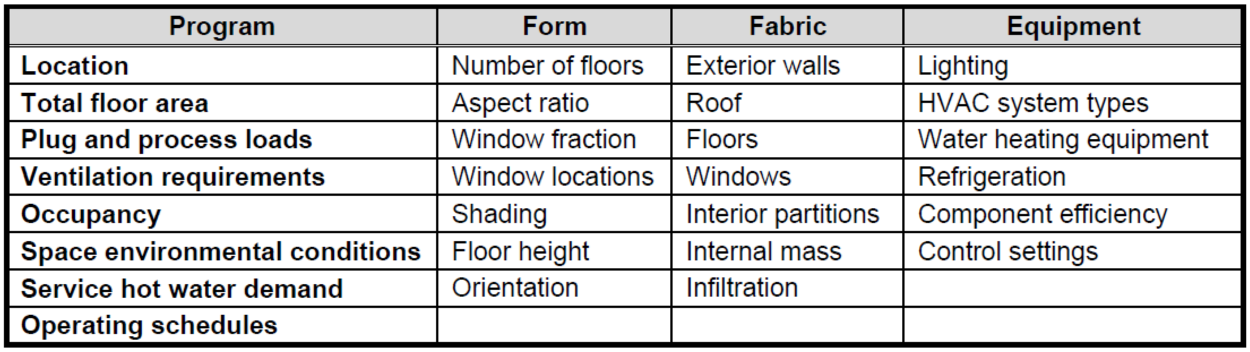
Both of the models have slightly different control schemes due to the fact that the primary focus of the heating model is to study boiler cycling, while the cooling model is intended to provide insight into load shaping and demand reduction.

## 2.2 Input Thermal Load

The U.S. Department of Energy (DOE) has worked alongside the building industry in order to meet aggressive energy efficiency goals. Part of this initiative included the development of standard energy models for common commercial buildings in order to evaluate new energy efficiency technologies. The load data used in the current study originate from one such standard energy model for a retirement community located in the Northeastern United States.

In order for the energy model to provide realistic heating and cooling load data, numerous input parameters were taken into account. The following table details the considerations used to obtain the hourly thermal loads.

**Table 2.1: Building model characteristics [Heinz]**



| Program | Form | Fabric | Equipment |
|---|---|---|---|
| **Location** | Number of floors | Exterior walls | Lighting |
| **Total floor area** | Aspect ratio | Roof | HVAC system types |
| **Plug and process loads** | Window fraction | Floors | Water heating equipment |
| **Ventilation requirements** | Window locations | Windows | Refrigeration |
| **Occupancy** | Shading | Interior partitions | Component efficiency |
| **Space environmental conditions** | Floor height | Internal mass | Control settings |
| **Service hot water demand** | Orientation | Infiltration | |
| **Operating schedules** | | | |

The input parameters for the building model came from studies of data from the Commercial Buildings Energy Consumption Survey (CBECS) and standard practices from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

The end result is a reasonable approximation of hourly thermal loads specific to building type and location. Dumortier et al conveyed the importance of hourly data in the simulation of TES systems. Hourly thermal load data collected from building energy models are becoming more accessible. The DOE study discussed in this section modelled 16 building types and 16 U.S. locations, directly characterizing 60% of commercial buildings. It has also become more common to construct building energy models to predict building performance and inform design decisions. As a result, a simulation approach to studying problems such as thermal system design and TES sizing can be conducted more accurately on a case by case basis. The particular load data (necessary boiler output) for each hour simulated in this study is depicted in the following figures.

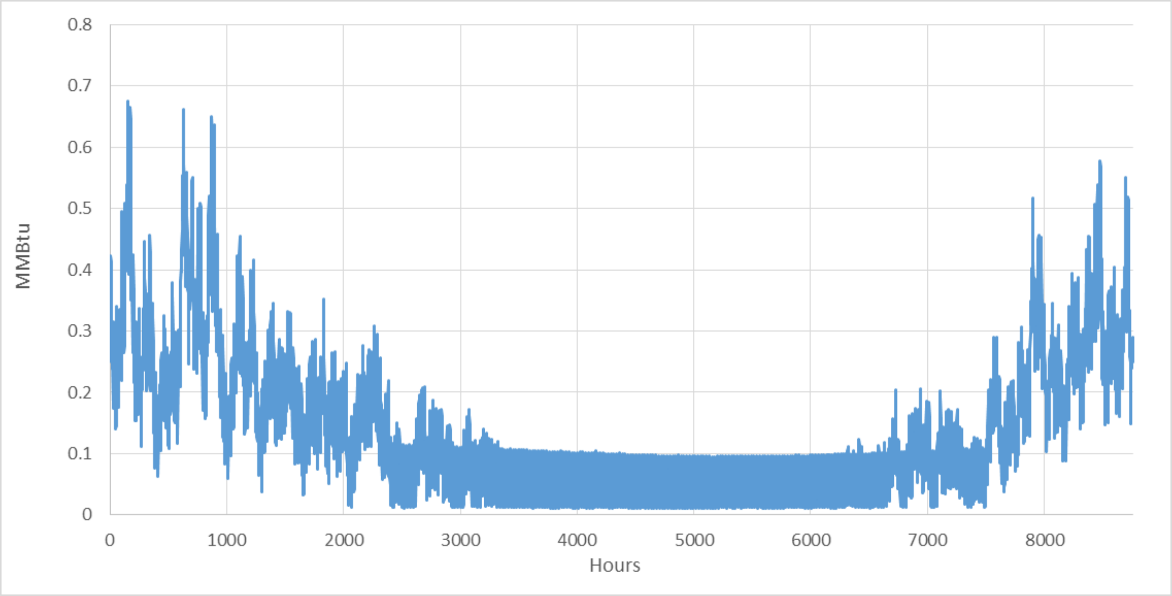


**Figure 2.3: Annual heating load curve**

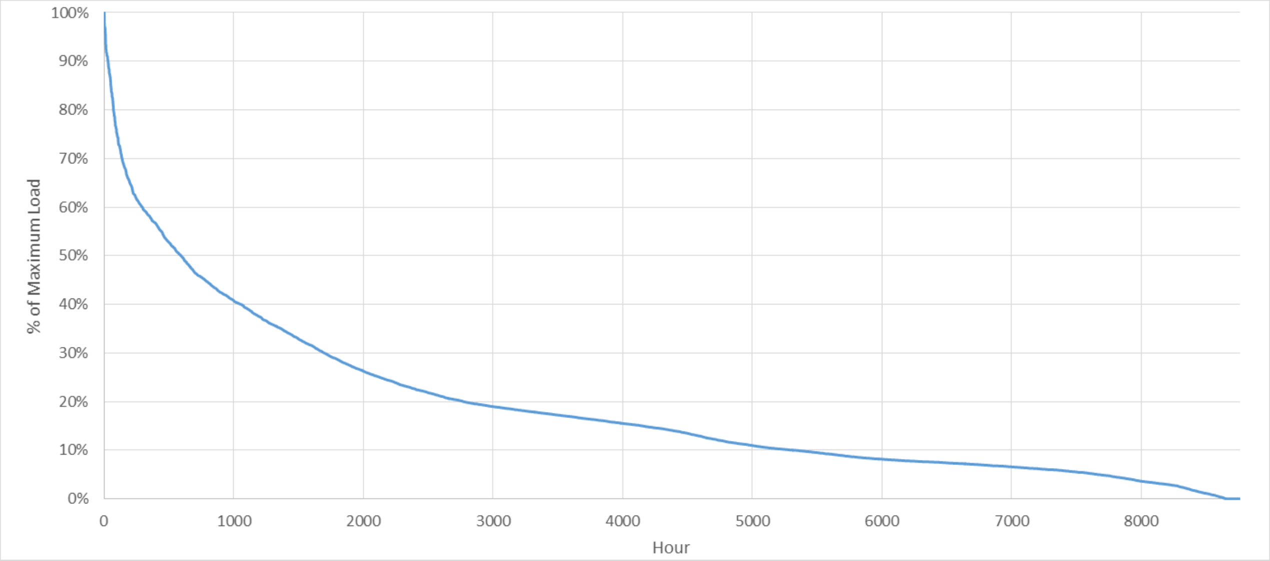


**Figure 2.4: Annual hourly heating load data used for simulation**

The peak boiler output is approximately 675 kBtu/hr with an annual average demand of 140 kBtu/hr and total heating load of 1,229 MMBtu/yr.  The highest peak heating loads occur during the beginning and end of the year due to low ambient temperatures and the resulting high demand for space heating.  The heat demand during the summer months are the result of the simulated hot water demand of the building model.  A simulation of the heating loop without storage and a modulating boiler capacity of 675 kBtu/hr indicates a required annual energy input of 1,430 MMBtu.

The cooling load data received from the model is interpreted in this study as the cooling output of the building's cooling system.  The highest cooling demand throughout the year is taken to be 277 tons, the average is 52 tons, and the total annual cooling load is 458,630 tons/yr.

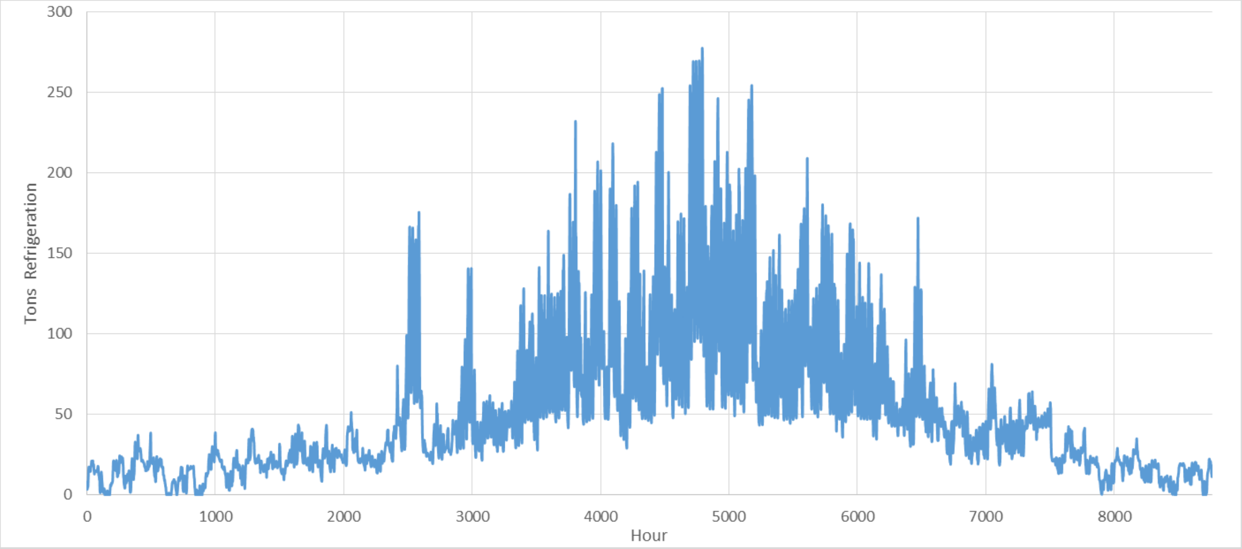


**Figure 2.5: Annual cooling load curve**

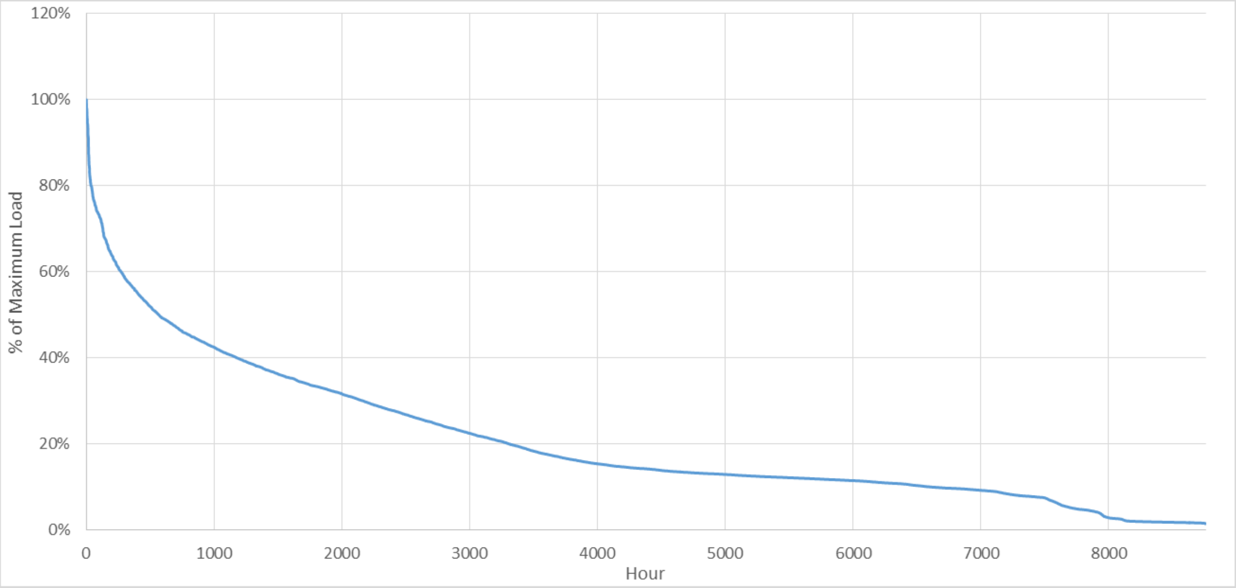


**Figure 2.6: Annual hourly cooling load data used for simulation**

Both the heating and cooling load data show that less than 7% of the hours in the year of data represent loads larger than 50% of the annual peak.  Similarly, less than 1% of the year accounts for thermal loads above 80% of the annual peak.  The data also suggests that more than half of the year is spent below 20% of the maximum load.

## 2.3 Methodology

The models built are reduced to their most basic components in order to produce a generalized assessment of TES sizing in a manner that can be quickly applied to a broad spectrum of thermal systems. Due to the simplicity of the models' controls, and the minimal number of inputted parameters necessary from the user, the model can be quickly adapted to provide a qualitative assessment of the implementation of TES by altering the inputted load data and boiler capacity according to the proposed system. The heating and cooling load data used for the simulations are taken to be the thermal output of the boiler or chiller. The preliminary models for each system are presented in order to provide context into the final design of the heating and cooling model. Both of the preliminary models utilize a stratified storage tank instead of separate return and supply tanks. It was ultimately decided that a separate return and supply tank would be optimal due to simplicity in controls and better management of supply and return temperatures.

## 2.4 Heating Model

### 2.4.1 Preliminary Model

The initial heating model was built with the primary focus of studying boiler cycling and comparison with previous work. The boiler model used in the simulation uses on/off controls and a stratified storage tank. Boiler operation is dictated by the average temperature of the constant volume storage tank which is maintained between 122 °F (50 °C) and 141°F (60 °C). Based on the average temperature of the tank, flow through the boiler-side of the system is either zero, or the flow necessary to fully load the boiler with the inlet water temperature from the tank and a temperature change of 19°F (10 K) across the boiler, chosen for ease of calculations and comparison with an existing study conducted by Heinz. The boiler setpoint and mass flow rate are given by the following equations:

$$\dot{m}_{boiler} = \frac{q_{capacity}}{\Delta T_{boiler} \times c}$$

$$T_{set} = T_{out} + \frac{q_{capacity}}{\dot{m}_{boiler} \times c}$$

Where,

$\dot{m}_{boiler}$ = Mass flow of water sent to the boiler from the tank; lb/hr

$q_{capacity}$ = Chosen nominal heating capacity of the boiler; Btu/hr

$\Delta T_{boiler}$ = Desired temperature difference of the flow through the boiler; 19°F (10 **K**)

c = Heat capacity of water; 1.00 Btu/lb*°F

The heating load data used in the simulation is taken as the thermal output of the boilers in the retirement community. It is assumed that this includes the power required for domestic hot water needs. Included in these assumptions is that the load dampening and phase lag resulting from the interaction between the thermal mass of the system boiler discussed by Heinz. Pumping losses and energy are neglected as well as standby storage losses. Exhaust energy from the boiler is considered in order to account for the energy lost from combustion and boiler inefficiencies.

The boiler capacity is initially sized to meet the peak heat demand of the year of hourly data, and uses non-modulating controls that turn the boiler on whenever the average tank temperature falls to 122 °F (50°C). The preliminary model of the heating system is depicted in Figure 2.7.

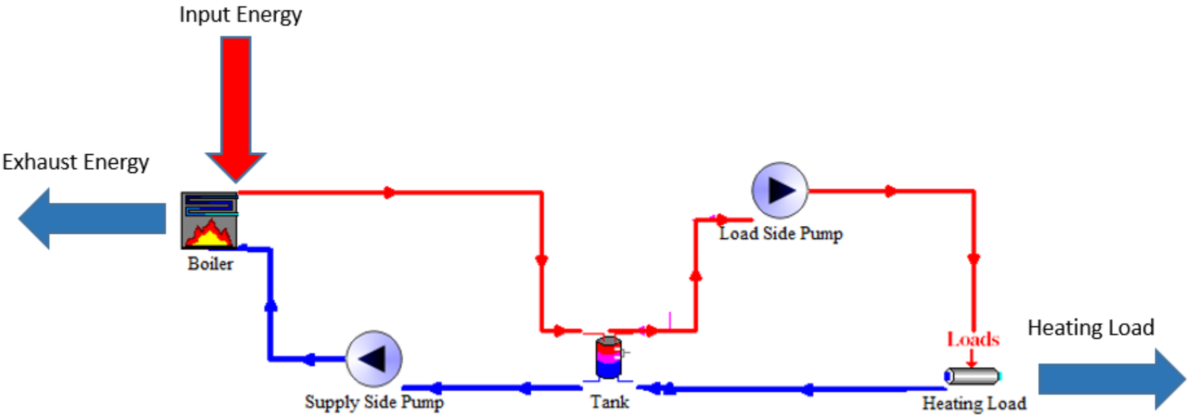


**Figure 2.7: Heating system model**

Flow on the load side of the system is modulated in order to maintain a 19 °F (10 **K**) degree temperature difference across the load. The mass flow of the load-side loop is given by the following equation:

$$\dot{m}_{load} = \frac{q_{load}}{c \times \Delta T_{load}}$$

Where,

$\dot{m}_{load}$ = Mass flow of boiler water being sent to the load; lb/hr

$q_{load}$ = Current heat demand of the load; Btu/hr

c = Heat capacity of water; 1.00 Btu/lb*° F

$\Delta T_{load}$ = Desired temperature difference of the flow across the load; 19°F (10°C)

The boiler setpoint is controlled in order to maintain the average tank temperature above the lower setpoint of 122°F (50 °C). The minimum is used as an indication that the system's thermal storage has been depleted. The boiler, and boiler-side pump shut off when the average tank temperature exceeds 141°F (60 °C).

The inputted load was scaled down in order to make results comparable to the study conducted by Heinz in terms of boiler cycling. Figure 2.8 below shows the load profile of the load used in the latter study, and the scaled load profile used in this study.

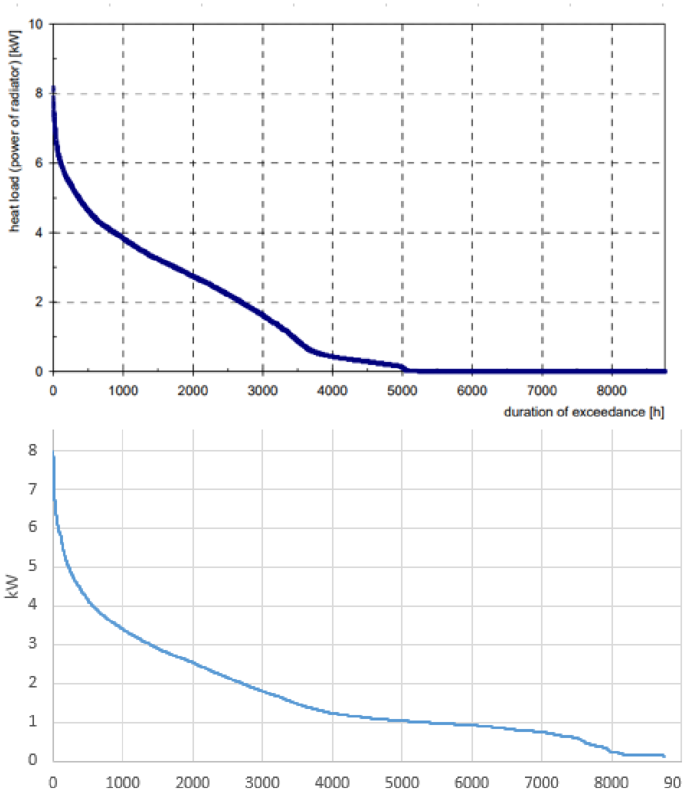


**Figure 2.8: Load profile comparison with Heinz**

### 2.4.2 Preliminary Results

The simulation was run with varying storage volumes for boilers of different sizes. The following figures illustrate the relationship between the storage volume, and the number of boiler cycles for boilers of different capacities for this simulation (Figure 2.9), and the simulation built by Heinz (Figure 2.10).

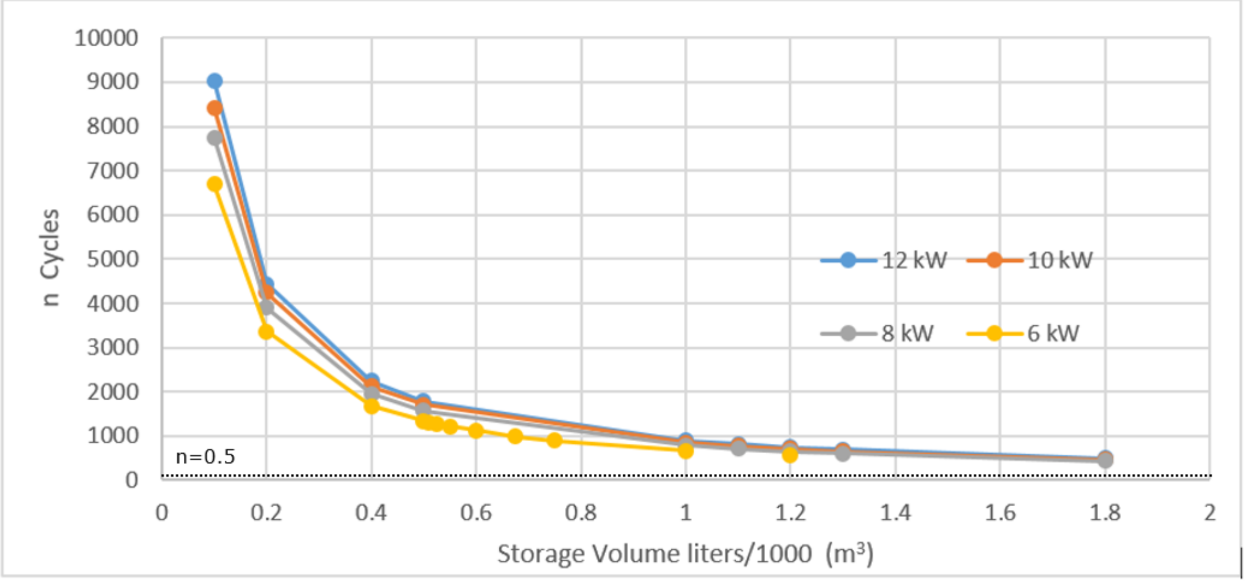


Figure 2.9: Preliminary boiler cycle reduction results for heating model

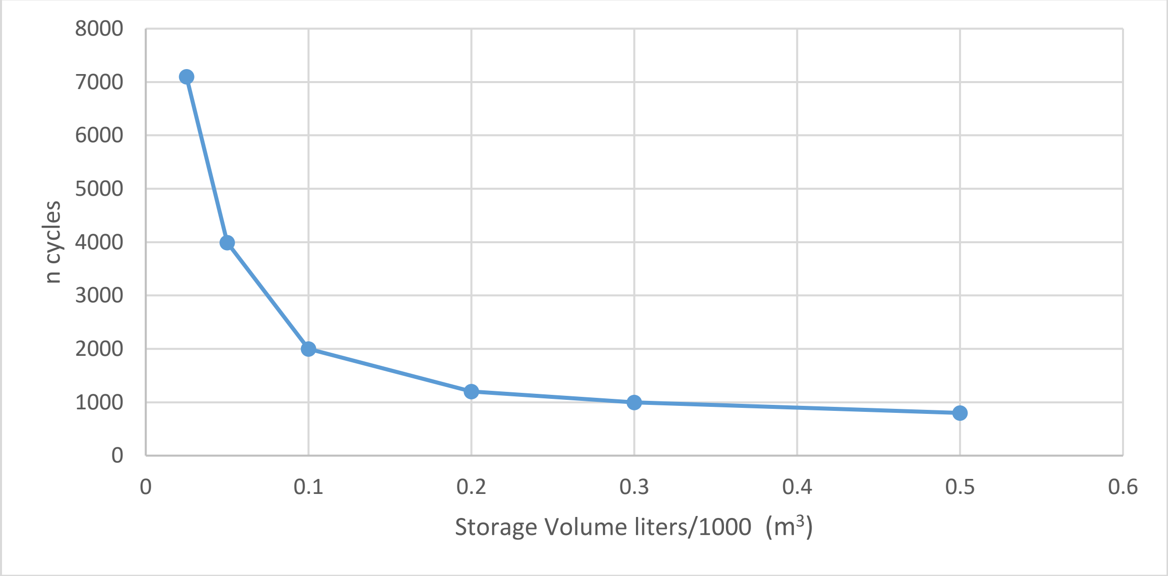


Figure 2.10: 12 kW Boiler cycle reduction exhibited in Heinz study

The tank volume corresponding to the base case without added storage is taken to be the minimum possible input for volume required for the model to run, or 15 liters (4 gallons). According to the results of the simulation, the number of boiler cycles drops drastically at small storage volumes. This decrease becomes less pronounced as greater storage volume is added. An increase from 100 liters (26.5 gallons) to 200 liters (53 gallons) of storage results in a 50% decrease in boiler cycling relative to the system with 100 liters. The dotted line indicates the theoretical minimum number of boiler cycles given an exceedingly large water volume. In such a case, the boiler would operate throughout the year and never switch off.

The diminishing returns on increasing storage volume with respect to boiler cycling is also exhibited in the data collected from the simulation conducted by Heinz. However, the storage volume at which the number of boiler cycles drop drastically occurs at smaller storage volumes than in the study by Heinz. The difference between the two sets of results are explained by the inclusion of thermal capacitance of components outside of the TES tank volume in the older study. More specifically, Heinz factors the thermal capacity of the boiler and radiator into the effects on cycling without subtracting the equivalent water storage volume from the TES volume. As stated in his paper, the boiler and radiator have an equivalent thermal capacity of 7 liters and 83 liters of water storage, respectively. Furthermore, the temperature difference across the system used in Figure 2.10 is twice as large as the temperature difference across the current simulation. These factors are accounted for in the following figure, where the two simulation results are compared by plotting the cycle reduction of both studies against the same effective TES volumes.

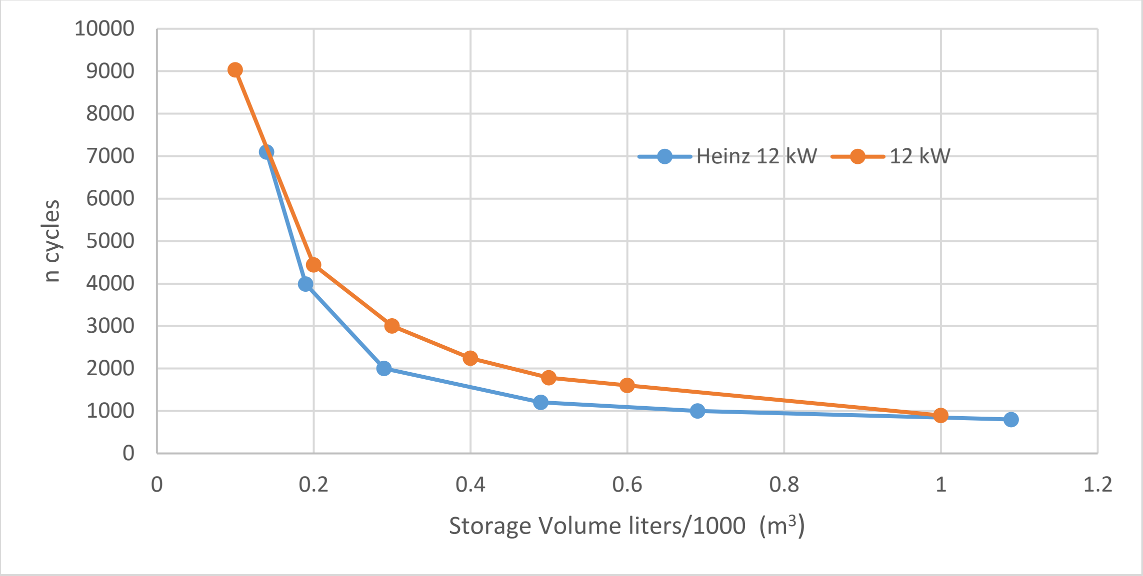


**Figure 2.11: Boiler cycle reduction direct comparison**

2.4.3 Revised Heating Model

The revised heating model employs the setup described in Figure 2.7 where a return and supply storage tank are utilized and supply and return temperatures are maintained at 140 $^{o}$F (60 $^{o}$C) and 130 $^{o}$F (54.4 $^{o}$C), respectively. These changes aid in the comparison between the heating and cooling model data. In most practical situations, boilers are able to modulate down to about 40% of their maximum load. This allows the boiler to follow the heating demand to a fraction of its full load capacity. In the context of this study, the added flexibility provided by a modulating boiler allows the boiler to be operated continuously before the storage is either fully depleted or charged, thereby decreasing the number of annual boiler cycles

In order to represent this capability in the heating model, the controls were altered to allow the boiler to match the heating load data whenever the heat demand is at least

40% of its maximum capacity. When the heating demand falls below 40% of the boiler capacity, the boiler remains on, operating at 40% part load until the storage tank is fully charged and the boiler cycles off. The load is then met by the stored hot water until the tank is emptied, at which point the boiler turns on and operates between 40% and 100% of full load depending on the building's demand.

A separate control scheme was constructed in order to examine the effect of storage capacity on minimum necessary boiler capacity. In this regime, storage is maintained at its maximum volume whenever the load is within the boiler capacity. The storage is only dispatched when the heating load exceeds the capacity of the boiler. The boiler capacity for each storage volume is reduced until the minimum capacity required to keep the tank temperature above the minimum setpoint throughout the year is reached. The following figure demonstrates this operating strategy during the annual peak heating load.

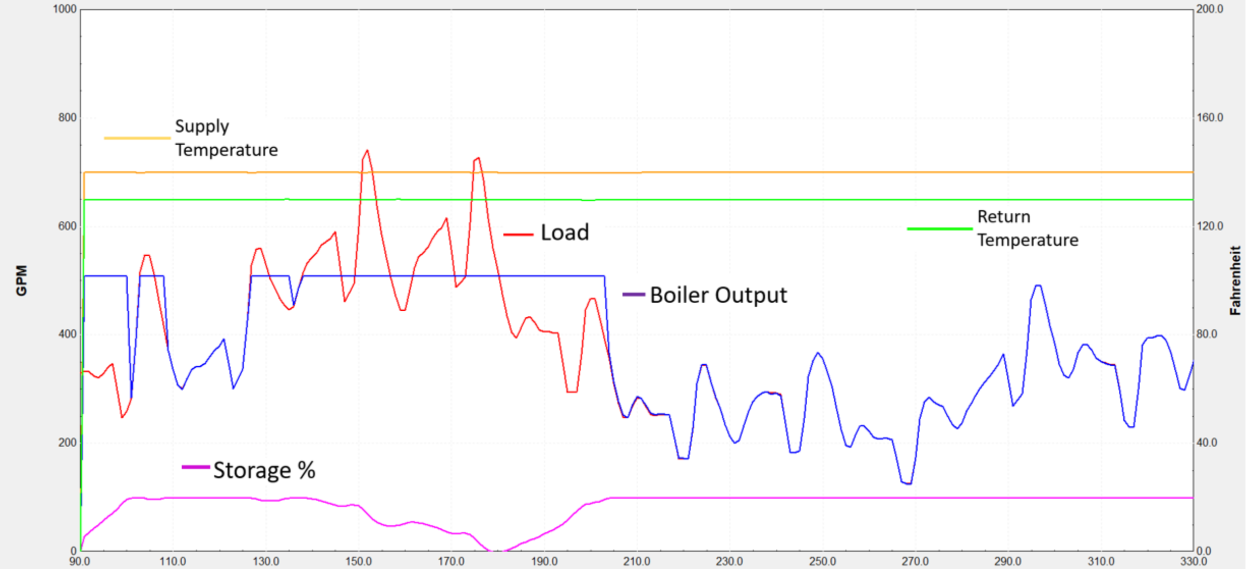


**Figure 2.12**: **Hot water storage system with reduced boiler capacity and 52,834 gallons (200 m$^3$) storage**

In the previous figure, initial flow through the boiler to the storage tank is maintained at the boiler's maximum capacity until storage reaches 100%. Once the storage is at full volume, the boiler output flow matches the flow through the load until the load flow increases above the maximum capacity of the boiler. When this occurs, stored hot water is dispatched in order to help the boiler meet the heating load. Throughout this period, the boiler flow is maintained at full capacity, and continues to do so until the storage is fully charged once more.

## 2.5 Cooling Model

The control strategy for the cooling model is centered on a rate schedule taken from the electric utility associated with the location of the load data. The rate schedule is imposed on the system with a forcing function (Type14h) which indicates on peak and off-peak periods to the controls. Peak hours occur for 8 hours from 12 pm to 8 pm.

The energy model uses separate return and supply tanks instead of a stratified storage tank. In doing so, the outlet chilled water temperature from the chiller can be maintained at a constant setpoint of 44 $^{o}$F (6.7 $^{o}$C) which is the saturation temperature of 70 $^{o}$F (21.1 $^{o}$C) air at 50% relative humidity. The diagram of the model is pictured below in Figure 2.13

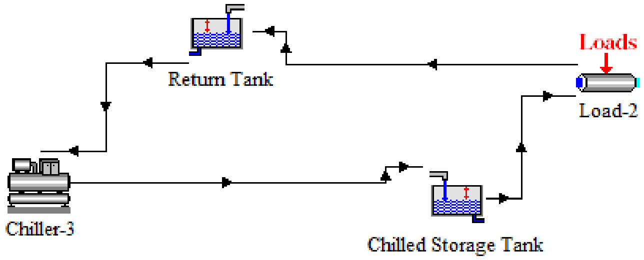


Figure 2.13: Chilled water storage model diagram

In this regime, storage level is addressed as a percentage of the maximum storage volume. The return tank volume is equal to the storage tank volume so that the storage can be completely discharged without the need for recirculation of excess flow and the system can remain closed. The total storage volume refers to the combined volume of the return and supply tanks.

### 2.5.1 Chiller Load Shaping

At the beginning of each off-peak period, the chiller is fully loaded in order to bring the chilled storage to 100% of the maximum volume. Once this is accomplished, the cooling output of the chiller matches the load at each timestep in order to ensure that the storage is fully charged at the beginning of each on peak period. When the on peak period begins, the storage is dispatched at an equal rate over the 8-hour peak period so that the chilled storage is completely empty at the end of the on peak period except for the chilled water volume necessary to satisfy the cooling load at the proceeding timestep.

Figure 2.14 illustrates how the cooling system operates during 10 days in the month of October when loads are at their largest.

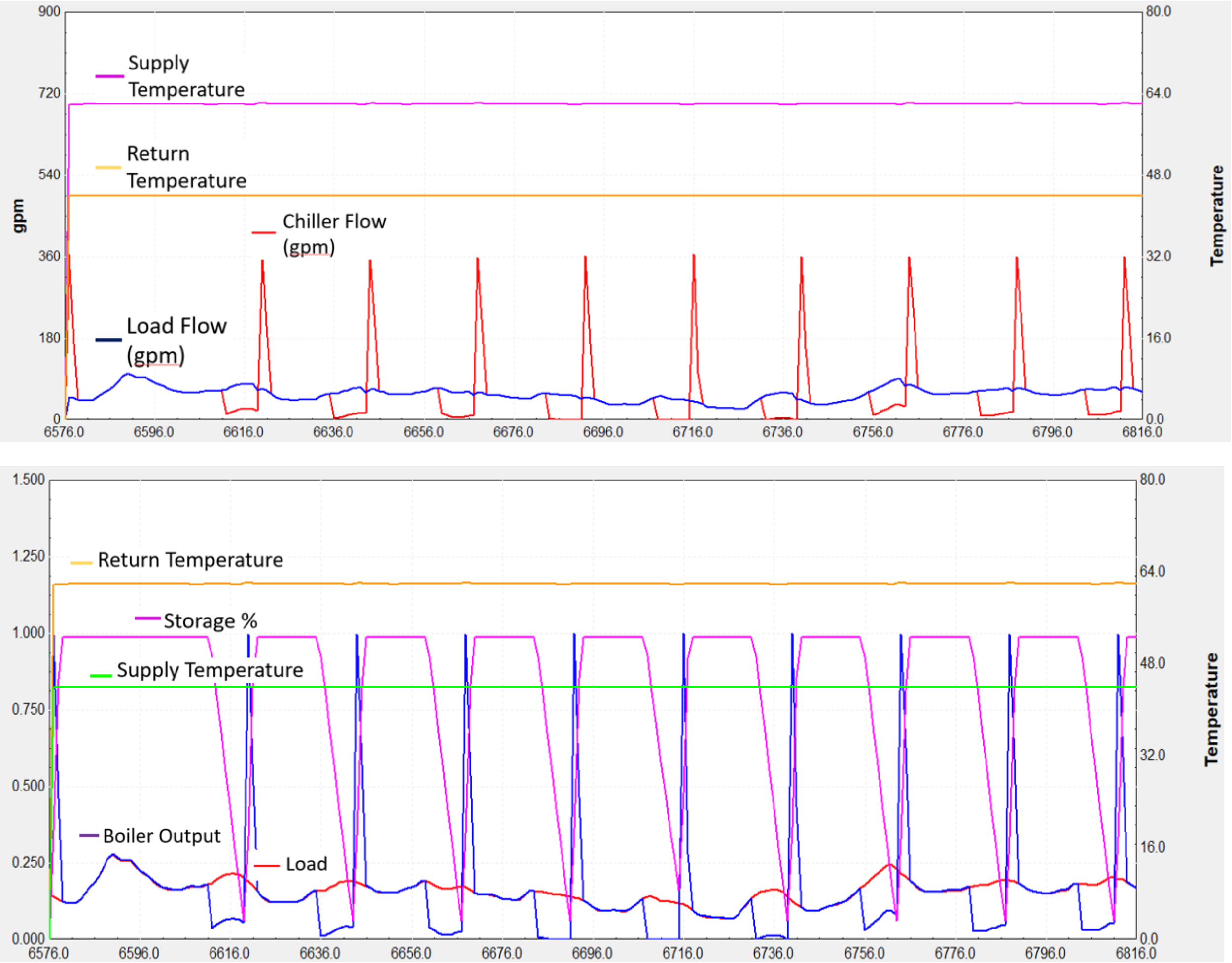


**Figure 2.14: Chilled water storage system operation during 10 days in October with 52,834 gallons (200 m$^3$) of storage.**

The return and supply temperatures of the system during this period are maintained at 54 °F (12.2 °C) and 44 °F (6.7°C) respectively and the on peak load is almost completely eliminated.

### 2.5.2 Minimum Chiller Capacity

It is necessary to deviate from the control strategy described above when simulating systems with reduced chiller capacity since the storage must be utilized in a way that allows the system to satisfy peak demands that are larger than what the chiller can supply by itself. During peak cooling periods in simulations with reduced chiller capacity, the chiller is set to run at full capacity for as long as necessary and the stored cooling is only dispatched when the cooling load exceeds chiller capacity. This behavior is illustrated for a system with 27% chiller capacity reduction from the annual peak load and 52,834 gallons (200 m$^3$) of storage during 10 days in July in Figures 2.15.

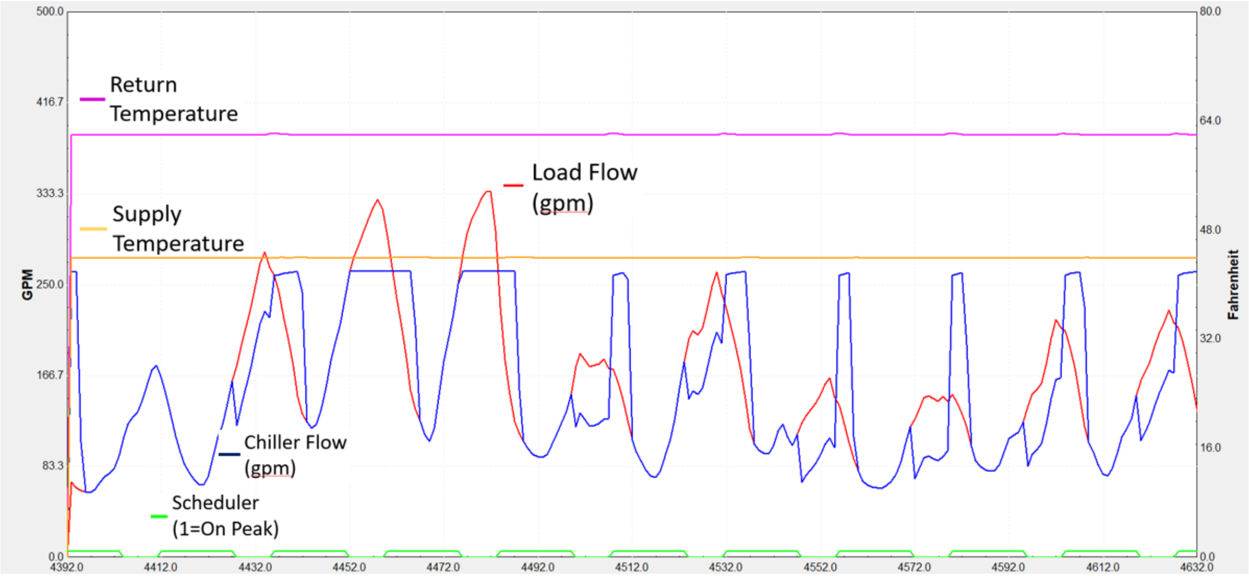


**Figure 2.15: Chilled water storage operation during annual peak cooling load with reduced chiller capacity.**

The Load Flow in Figure 2.15 is the flow entering the load from the storage tank. The flow from the storage is determined by a 10 $^{o}$F (5.5 K) temperature increase across the load.  The addition of storage in the above case allows the temperature difference to be maintained even when the cooling load exceeds the maximum capacity of the chiller. This is best exemplified in the 3rd and 4th peaks when the necessary load flow exceeds the maximum possible flow through the chiller.  The extra chilled water capacity necessary is provided by the storage and the temperature difference across the load is maintained.  The scheduler indicates the on peak periods.

The following figure depicts a comparison between the chiller operation of the same system and a system without storage and a full capacity chiller.

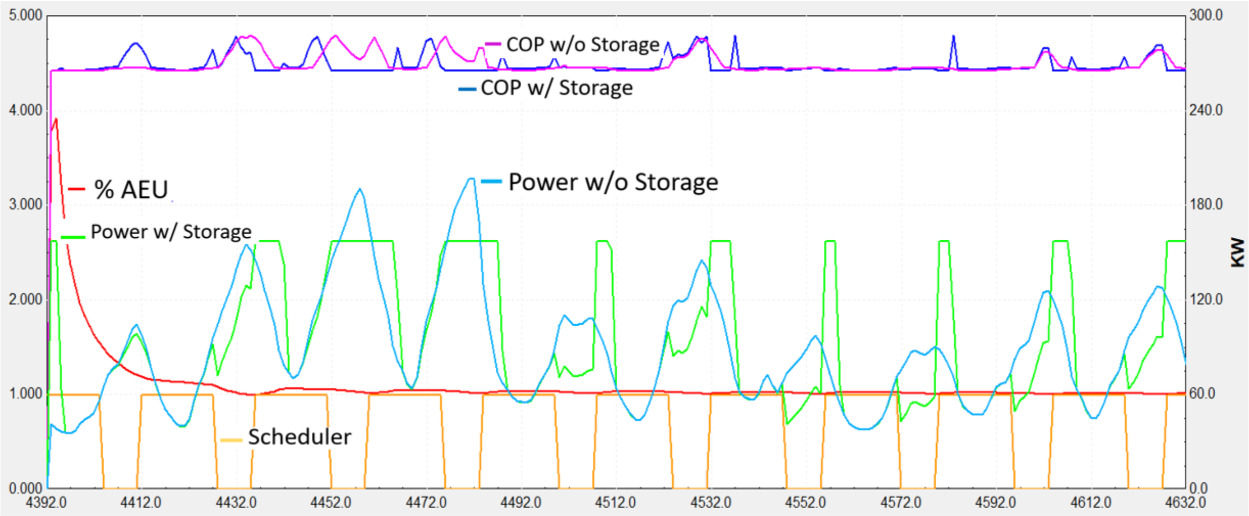


**Figure 2.16:  Chiller behavior comparison during 10 day period in June with and without chilled water storage**

The %AEU (red) depicts the percent of energy usage of the chiller with storage divided by the energy usage of the chiller without storage and is a reflection of the shifting Coefficient of Performance (COP), or cooling output divided by the energy consumed by the chiller, of each system throughout each scheduling cycle.  Depending on the capacity of the chiller in the storage system, the chiller may consume more or less energy throughout the year in comparison with the chiller sized to meet the maximum peak demand in the simulation without storage. Since the only power consumption that the simulations are concerned with occur in the chiller, this difference is a function of their respective part load efficiencies. The part load performance curve used in the chiller models remains consistent for each capacity simulated. The COP of the chillers remains at 4.425 under a PLR of 25% and is linearly interpolated between the points on the following figure.

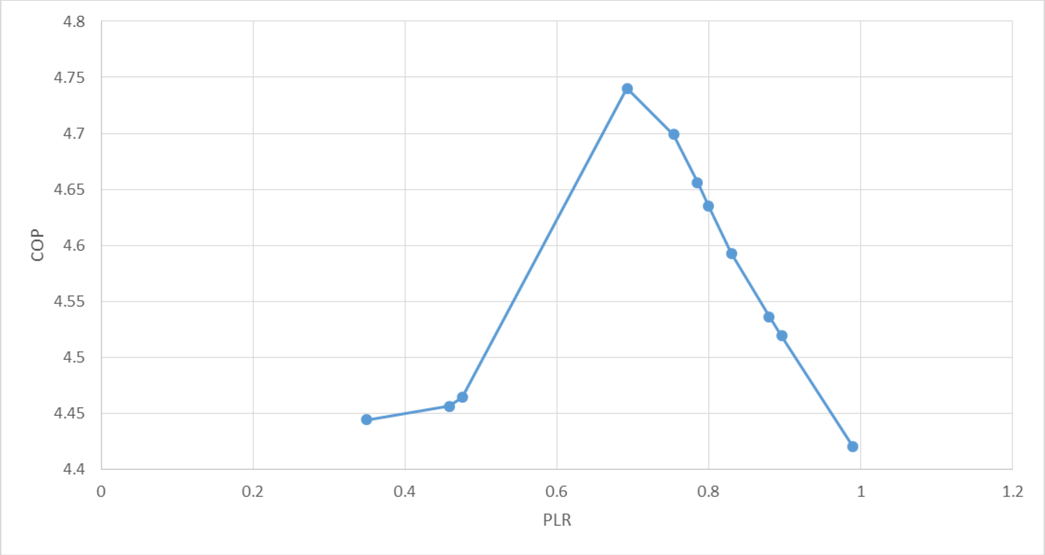


**Figure 2. 17: Chiller part load efficiencies above 25% part load**

Regardless of the chiller's capacity, optimal cooling occurs at approximately 74% part load. As a result, net energy savings with a reduced chiller capacity typically occur during the shoulder months during the simulations, and decrease during the peak cooling season as evidenced by Figure 2.18 which depicts the net power consumption difference between the two systems with a storage system simulated with a 72% cooling capacity and about 105,670 gallons (400 $m^3$) of storage. It should be noted that the chiller operation of these simulations were not specifically optimized with respect to the part load efficiency curve of the chillers. The annual energy consumption increase in this scenario was simulated to be 468 kWh.

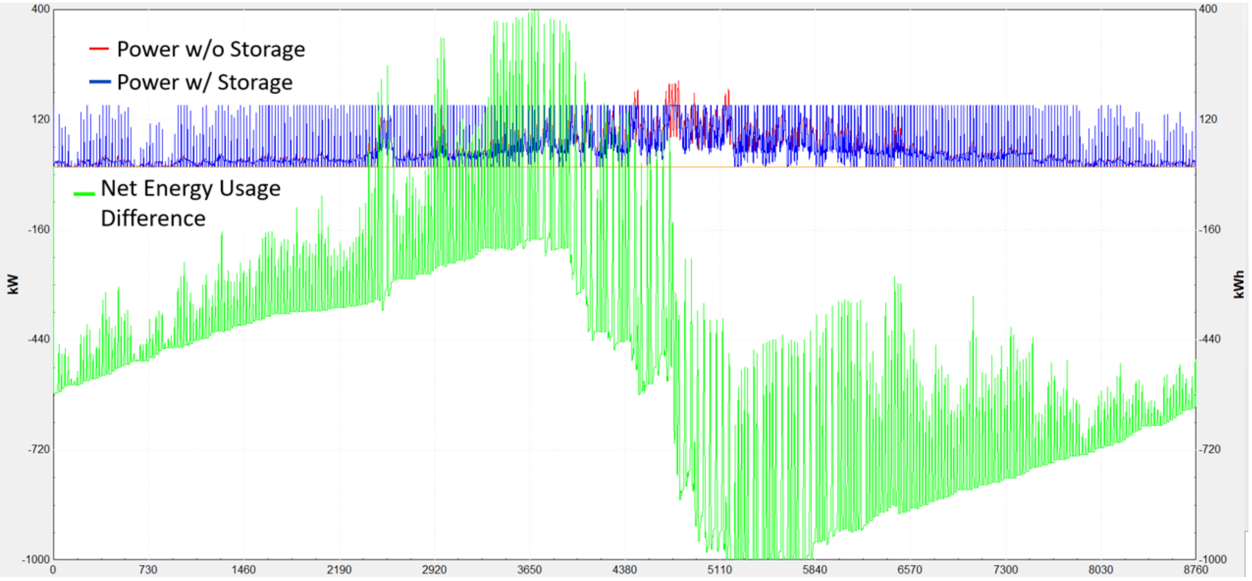


**Figure 2.18 Difference in energy consumption for cooling with a 72% capacity chiller and 105,670 gallons of storage**

# CHAPTER 3

# RESULTS AND DISCUSSION

## 3.1 Boiler Cycles

The heating model was run with the original hourly unscaled heating load associated with the retirement community energy model heating load data. The load data has a peak load of about 0.67 MMBtu/h. In this simulation, the boiler was allowed to modulate from 100% to 40% of its rated capacity, which is sized to meet the annual peak heating load. The following figure depicts the number of boiler cycles against varying storage volumes.

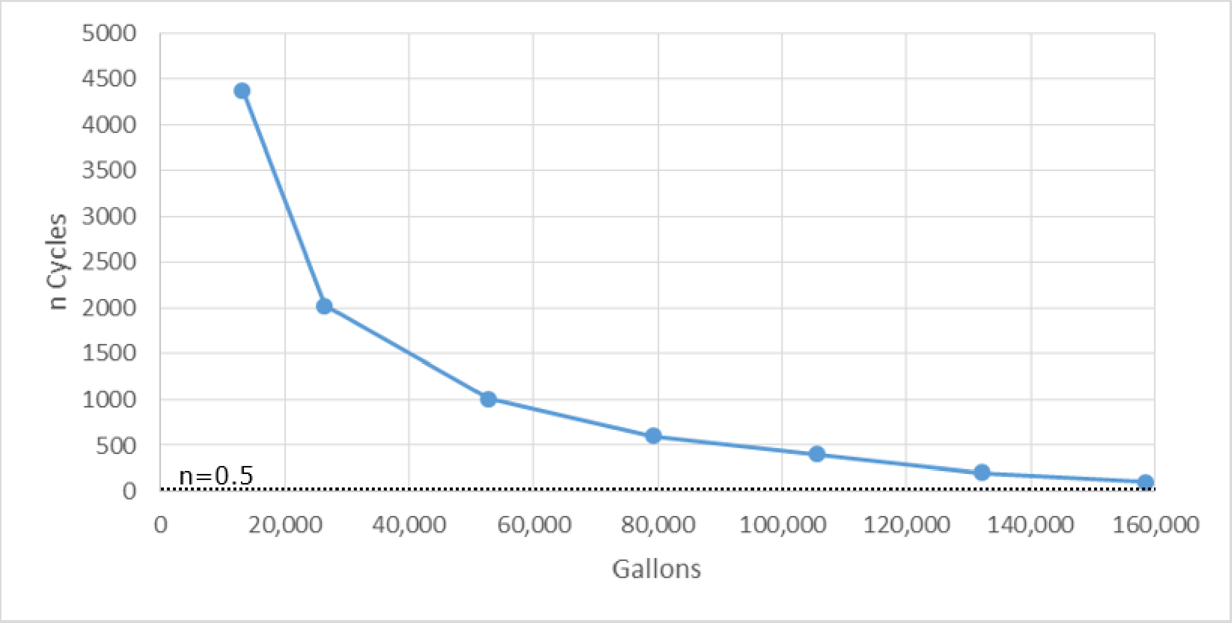


Figure 3.1: Annual boiler cycles with respect to total storage volume

Boiler cycle reduction per unit of storage volume rapidly diminishes as volume increases. The results also appear to be consistent with the idea that boiler cycles should approach 0.5 as the storage volume becomes so large that it is never fully depleted once charged. According to the model results, this point is reached at approximately 14 million gallons.

The frequency of boiler cycling increases the further the heating load falls below the minimum output capacity of the boiler of 40%. The length of each cycle increases proportionally to the TES volume tested.

The annual average part load ratio of the boiler changes negligibly, decreasing from 43.7% to 43.6% as the storage volume was increased to 158,503 gallons (600 $m^3$) from the case without storage. Additionally, the percent of the year that the boiler is on is not perceived to change with storage volume.

## 3.2 Minimum Boiler Capacity

The ability to reduce boiler sizing from implementing various capacities of TES was examined by reducing the boiler capacity for each volume until the minimum capacity required to maintain the 10 $^oF$ (5.6 K) temperature difference across the load is found. The supply and return tank temperatures are maintained at the 140 $^oF$ (60 °C) and 130 $^oF$ (54.4 °C) setpoints, respectively by matching the boiler output to the heating load. The supply and return tank each represent half of the total storage volume. When the heating load exceeds the boiler capacity, the stored hot water is discharged. As soon as the heating load falls within the maximum capacity of the boiler, the storage is charged by maintaining the boiler at full capacity until the tank is filled.  The following figure depicts the reduction in necessary boiler capacity with increasing storage volumes.

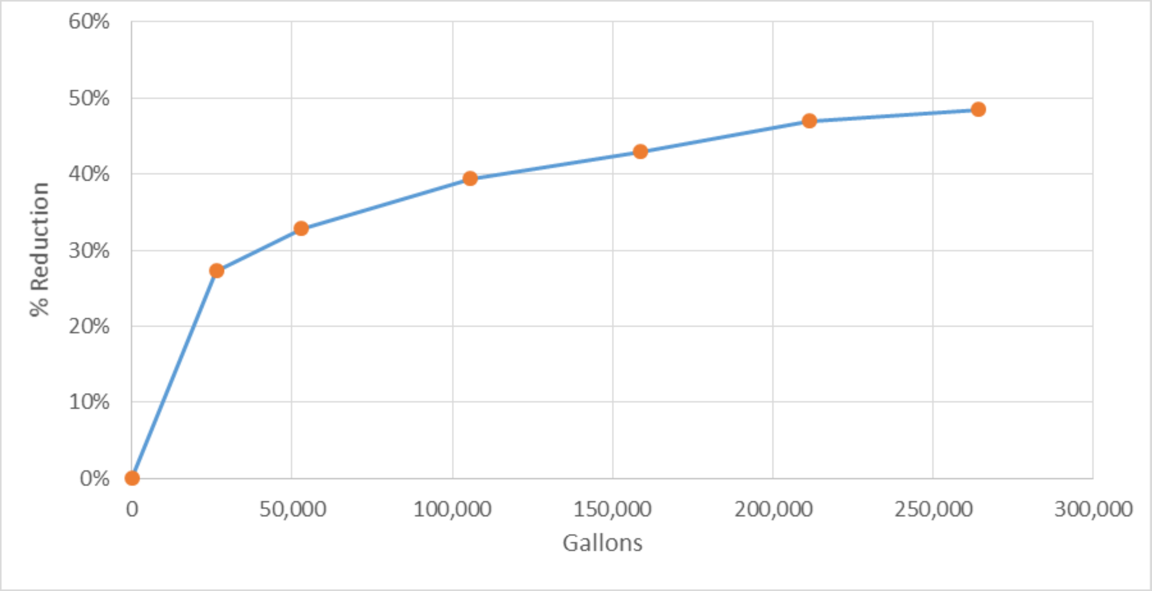


**Figure 3.2: Boiler capacity reduction from peak heat demand with increased storage volume.**

The minimum necessary boiler capacity was reduced by 48%, from 676 kBtu to 348 kBtu/hr with the addition of 264,172 gallons (1,000 $m^3$) of total storage volume. This equates to a reduction of about .125 kBtuh/hundred gallons of added storage.  The most marked decrease in necessary boiler capacity was achieved in the first 26,417 gallons (100 $m^3$) of storage which allowed boiler capacity to be reduced by 27%; a capacity reduction of .695 kBtu/hundred gallons.  Further increases to storage volume results in smaller reductions in necessary boiler capacity.  An increase of 211,338 gallons (800 $m^3$) to 264,172 gallons (1,000 $m^3$) only results in a 1.5% decrease in necessary boiler capacity.

## 3.3 Chiller Load Shaping

The ability for different volumes of TES to shift on peak cooling loads to the off peak period was studied using the cooling model. In order to keep the controls consistent for each storage volume, the same generalized control strategy was applied for each simulation with varying storage volumes. The controls ensured that the maximum capacity of storage was utilized during each cycle. This was accomplished by setting the controls to ensure that the storage was fully charged at the beginning of each on peak cycle and that cooling during the on peak is initially provided by the storage alone. In the event that the storage is depleted before the end of the on peak cycle, the chiller is used to satisfy the cooling load.

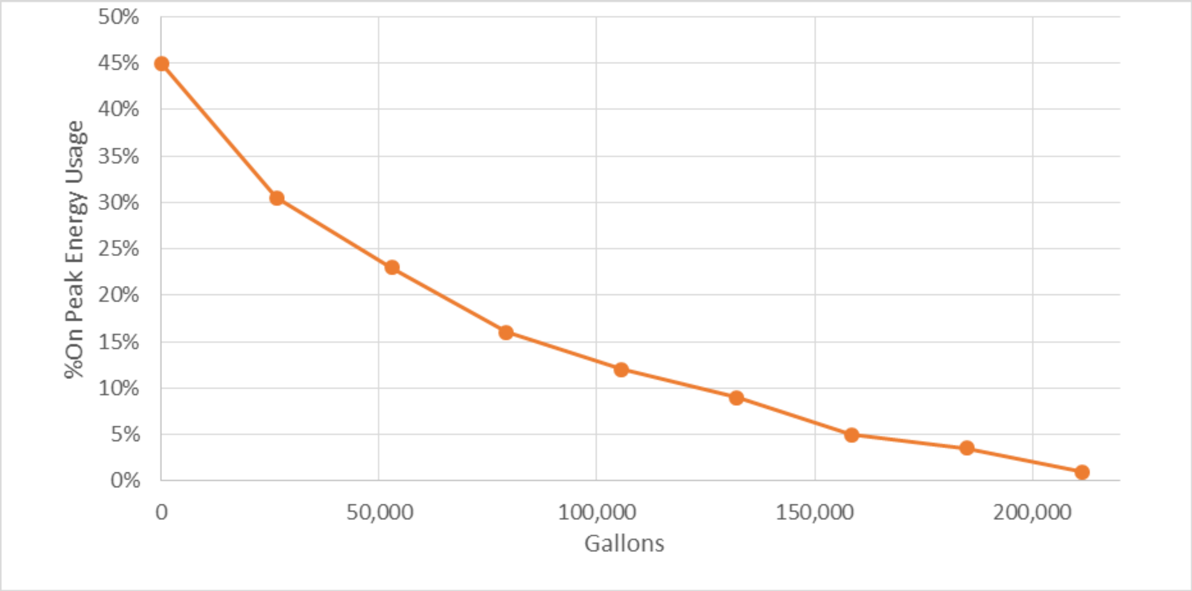


**Figure 3.3: Percent of annual energy usage consumed during on peak periods for varying storage volumes.**

Under operation without storage, 45% of total energy usage occurred during the on peak periods. The largest reduction in on peak energy usage per unit of volume occurs at initial volumes. With 211,338 gallons (800 $m^3$) of storage, 99% of the annual load is covered during the off peak period. Over 50% of the reduction of on peak energy usage is realized with the addition of 52,834 gallons (200 $m^3$) of storage. The diminishing returns in on peak energy use reduction with respect to added storage volume stems from the shape of the inputted load's duration curve. The thermal storage capacity of larger volumes is far greater than typically necessary throughout the year, and can only be fully utilized during the most extreme days.

## 3.4 Minimum Chiller Capacity

The effect of different TES volumes on the minimum necessary chiller capacity was studied in the same manner as discussed in Section 2.4 Revised Cooling Model. For each storage volume tested, the chiller capacity was decreased incrementally until the minimum capacity necessary to maintain the return water temperature below the 54 $^oF$ (12.2 °C) maximum and supply water at 44 $^oF$ (6.7 °C) throughout the year. Unlike the hot water storage model, the cooling model charges and discharges chilled water storage according to daily on peak and off peak scheduling. The storage is dispatched at a constant rate over each on peak period so that the entire chilled water volume stored is discharged by the end of the on peak period. In the case that the cooling load exceeds the cooling capacity of the chiller, the chiller is fully loaded and storage is dispatched only as necessary. Figure 3.4 illustrates the necessary storage volume to achieve a given percent reduction in chiller capacity from a chiller sized to meet the annual peak load.

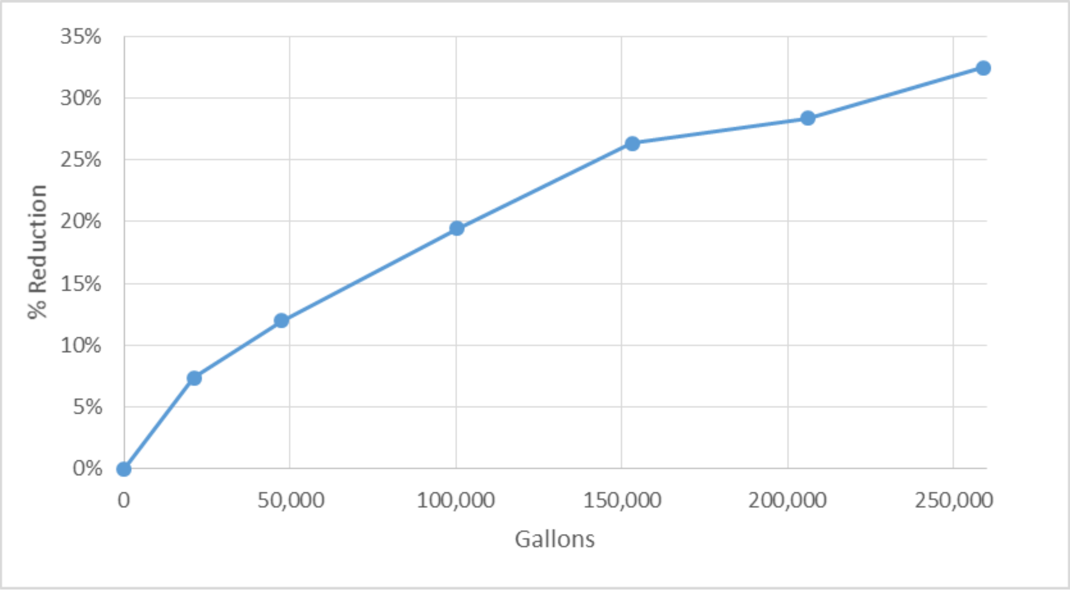


**Figure 3.4: Possible chiller capacity reduction accompanied by TES volume.**

The required chiller capacity decreases at a steady rate of about .16 kW/hundred gallons (.42 kW/ $m^3$) of storage. Ultimately, the addition of 264,172 gallons (1,000 $m^3$) of chilled water storage allows the chiller capacity to be reduced from 977 kW to 660 kW according to the data collected.

The following figure compares the possible percent capacity reduction in boilers and chillers for varying storage volumes.

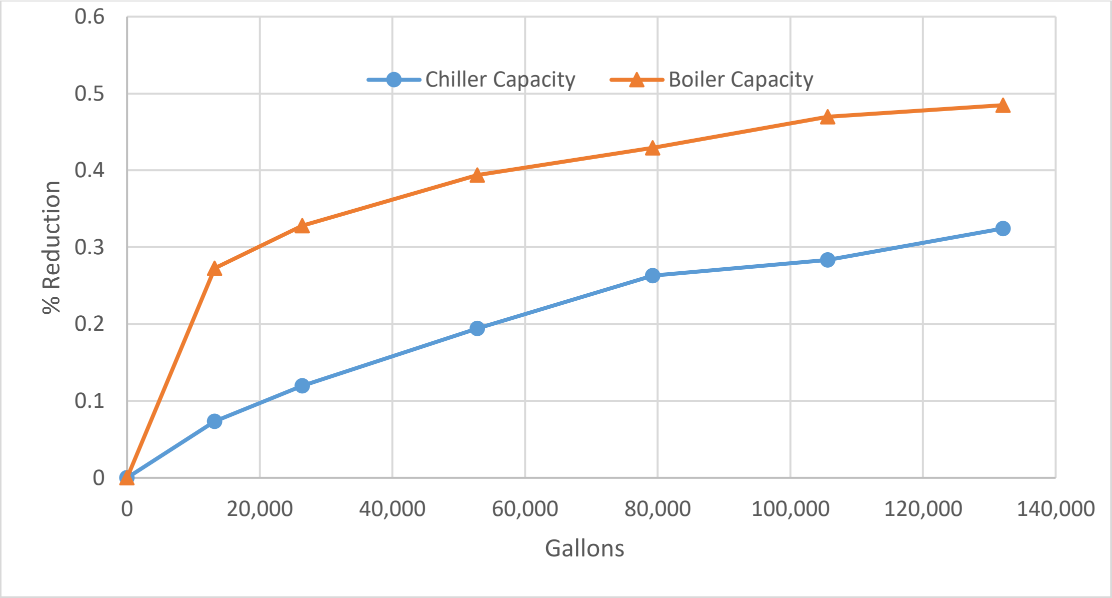


**Figure 3.5: Comparison between boiler and chiller capacity reduction with respect to TES volume.**

The addition of storage volume results in a larger percent reduction in the heating model because the magnitude of the annual peak heating load is significantly smaller than the annual peak cooling load. Thusly, smaller storage volumes for the heating model have the ability to satisfy a greater percentage of peak loads relative to the annual peak load from which the boiler or chiller is initially sized. The annual peak cooling load is 277 tons while the annual peak heating load is only 675 kBtu/hr, or 20% of the peak cooling demand. The following figure illustrates the possible reduction of boiler and chiller capacity in terms of kilowatts instead of percentage.

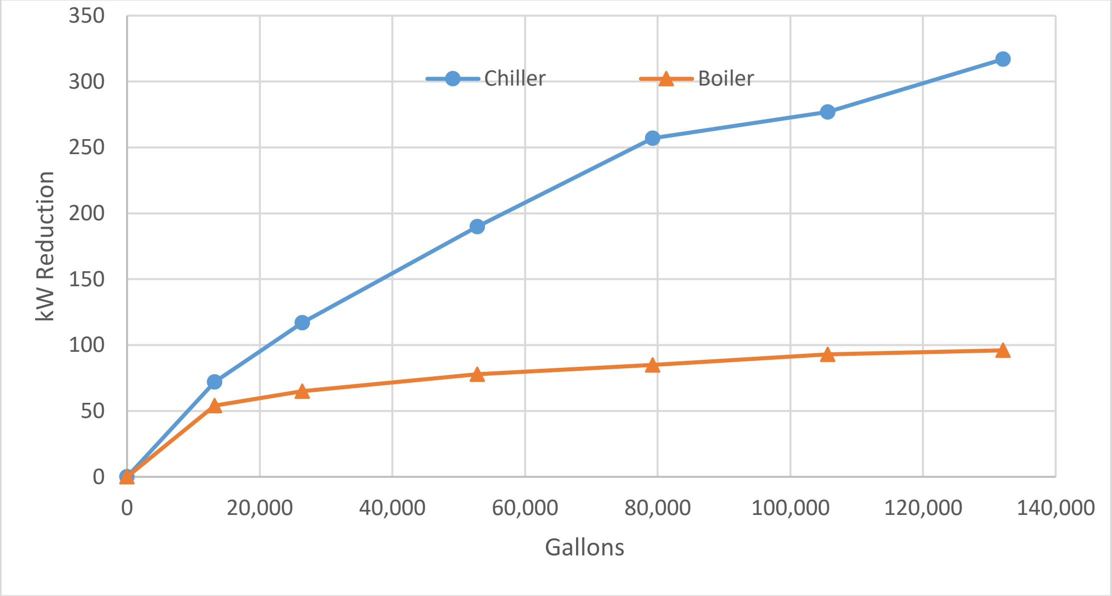


**Figure 3.6: Reduction in boiler and chiller capacity (kW) with the addition of varying TES volumes**

In practice, the addition of TES combined with a reduction in chiller and boiler capacity would be accompanied by a change in annual energy consumption. The added flexibility provided by the TES would allow the heating and cooling systems to operate in a more energy efficient manner. The boiler and chiller models calculate energy usage from efficiencies detailed in Appendix B for the boiler and Figure 2.15 for the chiller. The part load efficiencies used in the simulations vary marginally across the operating ranges of the boiler and chiller. Additionally, the controls used in the models did not specifically aim to optimize energy efficiency. As a result, a comparison between the supposed annual energy consumption of systems with differing storage capacities (illustrated in Figure 3.7) shows very little change with respect to overall annual energy consumption without storage implemented.

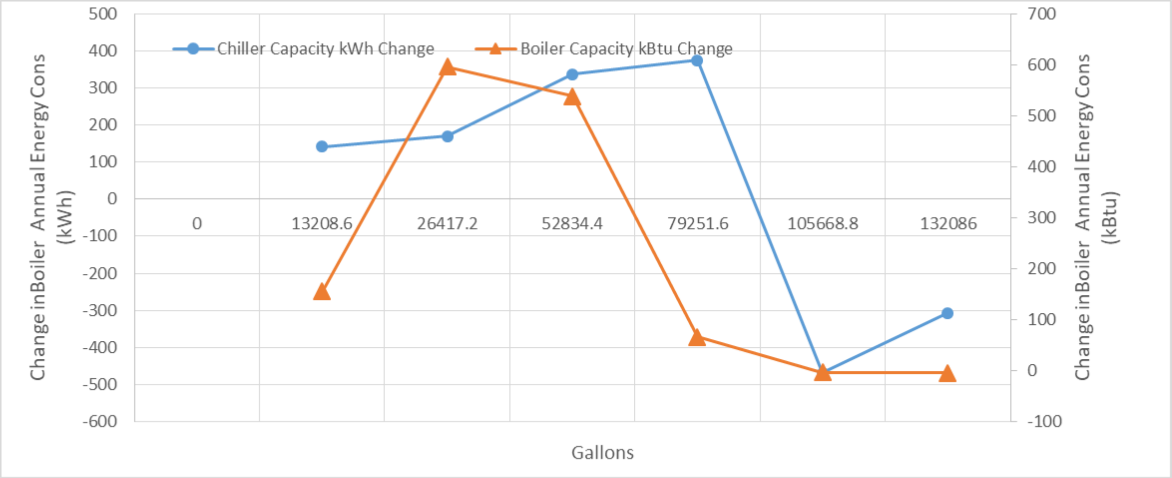


**Figure 3.7: Change in annual energy consumption for boiler (kBtu) and chiller (kW)models with added TES (gal)**

According to the figure above, the heating system achieves a peak change of 596 kBtu in fuel savings with 26,417 gallons (100 m$^3$), and a maximum increase of 4 kBtu at the largest volume tested of 132,086 gallons (500 m$^3$). The cooling system reaches the maximum increase in annual energy usage at the same volume of 132,086 gallons and the highest energy savings at 79,252 gallons (300 m$^3$) of storage with 374 kWh of energy reduction. These values are also small enough to be considered as rounding errors

# CHAPTER 4

# CONCLUSIONS

## 4.1 Summary

The scope of this research was to study the impact of varying thermal energy storage (TES) capacity on the design and operation of heating and cooling systems. This was accomplished through the modelling of separate heating and cooling water storage systems in simulation software, TRNSYS. The simulations in the study utilized hourly heating and cooling load data originating from a retirement community in New England. The models were created to be easily adapted to any inputted hourly load to provide an initial assessment for TES feasibility. In running the simulations with varying storage capacities, the relationship between storage size, boiler cycling and chiller load shaping was studied. The heating model showed that the addition of 13,209 gallons (50 $m^3$) of total storage reduced boiler cycling by 51%. Further increases to storage volume yielded smaller decreases in boiler cycles per unit of storage volume. Cycles reduced per hundred gallons of storage decreased from 8 n/hundred gal (21 $n/m^3$) for the addition of 26,417 gallons (100 $m^3$) of storage to 1.9 n/hundred gal (4.9 $n/m^3$) for the addition of 132,086 gallons (500 $m^3$) of storage. Results from the cooling model showed that on peak energy usage could be reduced from 45% to 23% with the addition of 52,834 gallons (200 $m^3$) of storage. 99% of on peak loads were able to be shifted to the off peak period at 211,338 gallons (800 $m^3$).

Further exploration of the implications of varying TES volumes included using TES to augment the effective capacity of heating and cooling systems. The heating and cooling models were simulated with reduced boiler and chiller capacities from what would typically be necessary to satisfy annual peak loads to study how TES may allow boilers and chillers to meet demands above their peak capacities. Results suggested that 26,417 gallons (100 $m^3$) of storage volume allowed the minimum capacity to be reduced by 7.4% for the chiller, and 27.3% for the boiler assuming that the minimum capacity for each is equal to their corresponding peak thermal load without storage.

## 4.2 Recommendations for Future Work

The research conducted in this study intentionally approaches TES storage capacity as a lump sum of thermal energy with no apparent restrictions on how it is stored or dispatched. To improve the practicality of the models created in this study, further detail should be specified in regards to the integration and controls of the TES in order to provide a more accurate representation of system efficiency as a result of TES of varying capacities. Such details may include the maximum heat transfer rate of the TES, additional pump energy consumption resulting from TES, standby losses, system demand reduction, the possibility of using multiple boilers or chillers and the impact of TES on the operating efficiencies of boilers and chillers, especially in the context of using TES to augment boiler and chiller capacity. After accounting for these characteristics of varying volumes of TES in the simulation control scheme, an estimate of annual energy consumption, cost and emissions would be possible. The proposed models used in conjunction with a contemporary study of TES technology and cost data would provide and extremely valuable tool for potential users of the technology.

# APPENDIX A
## TRNSYS INPUT FILES

### Heating Model

```
VERSION 17
***********************************************************************
********
*** TRNSYS input file (deck) generated by TrnsysStudio
*** on Saturday, January 26, 2019 at 08:48
*** from TrnsysStudio project:
C:\Trnsys17\MyProjects\Project4\HWStorage.tpf
***
*** If you edit this file, use the File/Import TRNSYS Input File
function in
*** TrnsysStudio to update the project.
***
*** If you have problems, questions or suggestions please contact your
local
*** TRNSYS distributor or mailto:software@cstb.fr
***
***********************************************************************
********


***********************************************************************
********
*** Units
***********************************************************************
********

***********************************************************************
********
*** Control cards
***********************************************************************
********
* START, STOP and STEP
CONSTANTS 3
START=0
STOP=8760
STEP=0.999999972
SIMULATION   START       STOP  STEP ! Start time      End time    Time
step
TOLERANCES 0.001 0.001             ! Integration      Convergence
LIMITS 30 500 50                   ! Max iterations  Max warnings
      Trace limit
DFQ 1                        ! TRNSYS numerical integration solver
method
WIDTH 80                     ! TRNSYS output file width, number of
characters
LIST                         ! NOLIST statement
```

```
                              ! MAP statement
SOLVER 0 1 1                        ! Solver statement      Minimum
relaxation factor Maximum relaxation factor
NAN_CHECK 0                   ! Nan DEBUG statement
OVERWRITE_CHECK 0             ! Overwrite DEBUG statement
TIME_REPORT 0                 ! disable time report
EQSOLVER 0                    ! EQUATION SOLVER statement
* User defined CONSTANTS


* Model "Heating Load" (Type 682)
*

UNIT 2 TYPE 682    Heating Load
*$UNIT_NAME Heating Load
*$MODEL .\Loads and Structures (TESS)\Flowstream Loads\Other
Fluids\Type682.tmf
*$POSITION 878 235
*$LAYER Main #
*$# Loads to a Flow Stream
PARAMETERS 1
4.190       ! 1 Fluid Specific Heat
INPUTS 5
12,1        ! Type39:Fluid temperature ->Inlet Temperature
12,2        ! Type39:Load flow rate ->Inlet Flowrate
LoadNeg           ! Equa:LoadNeg ->Load
0,0         ! [unconnected] Minimum Heating Temperature
0,0         ! [unconnected] Maximum Cooling Temperature
*** INITIAL INPUT VALUES
7 10000 28799997.869134 -999 999
*-----------------------------------------------------------------------
--------

* Model "Load Data" (Type 9)
*

UNIT 18 TYPE 9     Load Data
*$UNIT_NAME Load Data
*$MODEL .\Utility\Data Readers\Generic Data Files\Expert Mode\Free
Format\Type9e.tmf
*$POSITION 785 52
*$LAYER Outputs #
PARAMETERS 10
2           ! 1 Mode
0           ! 2 Header Lines to Skip
1           ! 3 No. of values to read
1.0         ! 4 Time interval of data
1           ! 5 Interpolate or not
43961       ! 6 Multiplication factor
0           ! 7 Addition factor
1           ! 8 Average or instantaneous value
40          ! 9 Logical unit for input file
-1          ! 10 Free format mode
*** External files
ASSIGN "\\Wdmycloudex2\iac\IAC\Andrew V\Thesis\Retirement Heating Load
MMbtuh.csv" 40
*|? Input file name |1000
```

```
*-----------------------------------------------------------------------
--------

* Model "Boiler" (Type 751)
*

UNIT 9 TYPE 751    Boiler
*$UNIT_NAME Boiler
*$MODEL .\HVAC Library (TESS)\Boiler\Efficiency from External
File\Type751.tmf
*$POSITION 454 362
*$LAYER Main #
*$# Boiler
PARAMETERS 5
367199.972831           ! 1 Rated Capacity
4.190        ! 2 Fluid Specific Heat
41           ! 3 Logical Unit for Data File
11           ! 4 Number of Inlet Temperature Points
2            ! 5 Number of PLR's
INPUTS 4
11,1         ! Type39-2:Fluid temperature ->Inlet Fluid Temperature
11,2         ! Type39-2:Load flow rate ->Inlet Fluid Flowrate
0,0          ! [unconnected] Input Control Signal
0,0          ! [unconnected] Set Point Temperature
*** INITIAL INPUT VALUES
100.0 1000.0 1 59.999997
*** External files
ASSIGN "C:\Trnsys17\Tess Models\SampleCatalogData\Boilers\Fluid
Boiler\Efficiency.Dat" 41
*|? Which file contains the external performance data for this boiler?
|1000
*-----------------------------------------------------------------------
--------

* Model "Boiler Aquastat" (Type 2)
*

UNIT 13 TYPE 2     Boiler Aquastat
*$UNIT_NAME Boiler Aquastat
*$MODEL .\Controllers\Aquastat\Heating Mode\Type2-AquastatH.tmf
*$POSITION 363 447
*$LAYER Controls #
*$# NOTE: This controller can only be used with solver 0 (Successive
substitution)
*$#
PARAMETERS 2
5            ! 1 No. of oscillations
250          ! 2 Safety limit temperature
INPUTS 6
0,0          ! [unconnected] Setpoint temperature
ind          ! Equa:ind ->Temperature to watch
0,0          ! [unconnected] High limit monitoring temperature
13,1         ! Boiler Aquastat:Output control function ->Input control
function-->Connect from output control signal
0,0          ! [unconnected] Turn on temperature difference
0,0          ! [unconnected] Turn off temperature difference
*** INITIAL INPUT VALUES
```

```
250 10.0 250 0 250 0
*------------------------------------------------------------------------
--------

* EQUATIONS "Cycle Count"
*
EQUATIONS 2
UF = [27,1]/(time+.0001)
cycles = (1-eql([25,1],[13,1]))/2
*$UNIT_NAME Cycle Count
*$LAYER Outputs
*$POSITION 64 298

*------------------------------------------------------------------------
--------


* Model "Boiler On Integrate" (Type 24)
*

UNIT 27 TYPE 24    Boiler On Integrate
*$UNIT_NAME Boiler On Integrate
*$MODEL .\Utility\Integrators\Quantity Integrator\Type24.tmf
*$POSITION 146 415
*$LAYER Outputs #
PARAMETERS 2
STOP        ! 1 Integration period
0           ! 2 Relative or absolute start time
INPUTS 1
13,1        ! Boiler Aquastat:Output control function ->Input to be
integrated
*** INITIAL INPUT VALUES
0.0
*------------------------------------------------------------------------
--------

* Model "Type661" (Type 661)
*

UNIT 25 TYPE 661   Type661
*$UNIT_NAME Type661
*$MODEL .\Controllers Library (TESS)\Delayed Inputs\Type661.tmf
*$POSITION 262 319
*$LAYER Outputs #
*$# The stickiness is set by the number of timesteps and not based on
the number of hours.
PARAMETERS 3
1           ! 1 Number of Inputs
1           ! 2 # of Timesteps to Hold Value
0.0         ! 3 Initial Function Value
INPUTS 1
13,1        ! Boiler Aquastat:Output control function ->Input Value
*** INITIAL INPUT VALUES
0.0
*------------------------------------------------------------------------
--------
```

```
* Model "Cycle Integrate" (Type 24)
*

UNIT 28 TYPE 24    Cycle Integrate
*$UNIT_NAME Cycle Integrate
*$MODEL .\Utility\Integrators\Quantity Integrator\Type24.tmf
*$POSITION 211 543
*$LAYER Outputs #
PARAMETERS 2
STOP         ! 1 Integration period
0            ! 2 Relative or absolute start time
INPUTS 1
cycles             ! Cycle Count:cycles ->Input to be integrated
*** INITIAL INPUT VALUES
0.0
*------------------------------------------------------------------------
--------

* Model "Type39-2" (Type 39)
*

UNIT 11 TYPE 39    Type39-2
*$UNIT_NAME Type39-2
*$MODEL .\Thermal Storage\Variable Volume Tank\Type39.tmf
*$POSITION 400 139
*$LAYER Main #
PARAMETERS 12
1            ! 1 Tank operation mode
10000        ! 2 Overall tank volume
0            ! 3 Minimum fluid volume
250          ! 4 Maximum fluid volume
15.0         ! 5 Tank circumference
4.0          ! 6 Cross-sectional area
0            ! 7 Wetted loss coefficient
0            ! 8 Dry loss coefficient
4.190        ! 9 Fluid specific heat
1000.0             ! 10 Fluid density
54.444467          ! 11 Initial fluid temperature
250          ! 12 Initial fluid volume
INPUTS 4
2,1          ! Heating Load:Outlet Temperature ->Inlet temperature
2,2          ! Heating Load:Outlet Flowrate ->Inlet flow rate
14,2         ! Type3b:Outlet flow rate ->Flow rate to load
0,0          ! [unconnected] Environment temperature
*** INITIAL INPUT VALUES
25.0 100.0 75.0 15.0
*------------------------------------------------------------------------
--------

* Model "Type39" (Type 39)
*

UNIT 12 TYPE 39    Type39
*$UNIT_NAME Type39
*$MODEL .\Thermal Storage\Variable Volume Tank\Type39.tmf
*$POSITION 632 351
*$LAYER Main #
```

```
PARAMETERS 12
1           ! 1 Tank operation mode
100000            ! 2 Overall tank volume
0           ! 3 Minimum fluid volume
250         ! 4 Maximum fluid volume
15.0        ! 5 Tank circumference
4.0         ! 6 Cross-sectional area
0           ! 7 Wetted loss coefficient
0           ! 8 Dry loss coefficient
4.190       ! 9 Fluid specific heat
1000.0            ! 10 Fluid density
60.000022         ! 11 Initial fluid temperature
250         ! 12 Initial fluid volume
INPUTS 4
9,1         ! Boiler:Outlet Fluid Temperature ->Inlet temperature
9,2         ! Boiler:Outlet Fluid Flowrate ->Inlet flow rate
16,2        ! Type3b-2:Outlet flow rate ->Flow rate to load
0,0         ! [unconnected] Environment temperature
*** INITIAL INPUT VALUES
25.0 100.0 23000 15.0
*-----------------------------------------------------------------------
--------

* Model "Type3b" (Type 3)
*

UNIT 14 TYPE 3     Type3b
*$UNIT_NAME Type3b
*$MODEL .\Hydronics\Pumps\Variable Speed\Type3b.tmf
*$POSITION 537 212
*$LAYER Water Loop #
PARAMETERS 5
30549.4           ! 1 Maximum flow rate
4.190       ! 2 Fluid specific heat
60.0        ! 3 Maximum power
0.05        ! 4 Conversion coefficient
0.5         ! 5 Power coefficient
INPUTS 3
0,0         ! [unconnected] Inlet fluid temperature
0,0         ! [unconnected] Inlet mass flow rate
bsig3       ! Equa:bsig3 ->Control signal
*** INITIAL INPUT VALUES
20.0 100.0 1.0
*-----------------------------------------------------------------------
--------

* Model "Type3b-2" (Type 3)
*

UNIT 16 TYPE 3     Type3b-2
*$UNIT_NAME Type3b-2
*$MODEL .\Hydronics\Pumps\Variable Speed\Type3b.tmf
*$POSITION 793 479
*$LAYER Water Loop #
PARAMETERS 5
30549.4           ! 1 Maximum flow rate
4.190       ! 2 Fluid specific heat
```

```
200         ! 3 Maximum power
0.05        ! 4 Conversion coefficient
0.5         ! 5 Power coefficient
INPUTS 3
0,0         ! [unconnected] Inlet fluid temperature
0,0         ! [unconnected] Inlet mass flow rate
sig         ! Equa:sig ->Control signal
*** INITIAL INPUT VALUES
20.0 100.0 1.0
*------------------------------------------------------------------------
--------

* EQUATIONS "Equa"
*
EQUATIONS 17
maxboiler = 711962.020077/197.767237*102
Vol = 250
maxload = 711692
sig = [18,1]/maxload
ind = [12,5]
bsig = (sig*le([18,1]/maxboiler,1)*ge([18,1]/maxboiler,.4)
+maxboiler/maxload*gt([18,1]/maxboiler,1))  +lt([22,9],Vol-
1)*maxboiler/maxload
LoadNeg = -[18,1]
bsig2 = bsig*(1-[13,1])+maxboiler/maxload*[13,1]
bsig3 = bsig2*le(bsig2*maxflow,bmaxflow)
+bmaxflow/maxflow*gt(bsig2*maxflow,bmaxflow)
BoilerGPM = [11,2]/3.79/60
LoadGPM = [12,2]/3.79/60
maxflow = maxload/4.19/(60-54.44)
bmaxflow = maxboiler/4.19/(60-54.44)
LoadkBtu = [18,1]/.947817/1000
BoilerkBtu = [9,3]/.947817/1000
dEU = ([29,6]-[9,6])*.947817/1000000
NSEUbtu = [29,6]*.947817/1000000
*$UNIT_NAME Equa
*$LAYER Main
*$POSITION 651 90

*------------------------------------------------------------------------
--------


* Model "Type65c" (Type 65)
*

UNIT 17 TYPE 65    Type65c
*$UNIT_NAME Type65c
*$MODEL .\Output\Online Plotter\Online Plotter With File\No
Units\Type65c.tmf
*$POSITION 465 490
*$LAYER Main #
PARAMETERS 12
3           ! 1 Nb. of left-axis variables
2           ! 2 Nb. of right-axis variables
0.0         ! 3 Left axis minimum
1000.0            ! 4 Left axis maximum
```

```
0.0         ! 5 Right axis minimum
1000.0            ! 6 Right axis maximum
1           ! 7 Number of plots per simulation
12          ! 8 X-axis gridpoints
0           ! 9 Shut off Online w/o removing
42          ! 10 Logical Unit for output file
0           ! 11 Output file units
0           ! 12 Output file delimiter
INPUTS 5
sig         ! Equa:sig ->Left axis variable-1
28,1        ! Cycle Integrate:Result of integration ->Left axis
variable-2
bsig2       ! Equa:bsig2 ->Left axis variable-3
11,1        ! Type39-2:Fluid temperature ->Right axis variable-1
12,1        ! Type39:Fluid temperature ->Right axis variable-2
*** INITIAL INPUT VALUES
Output cycles bsig returntemp supplytemp
LABELS  3
"Temperatures"
"Heat transfer rates"
"Graph 1"
*** External files
ASSIGN "***.plt" 42
*|? What file should the online print to? |1000
*-----------------------------------------------------------------------
--------

* Model "Type65c-2" (Type 65)
*

UNIT 19 TYPE 65    Type65c-2
*$UNIT_NAME Type65c-2
*$MODEL .\Output\Online Plotter\Online Plotter With File\No
Units\Type65c.tmf
*$POSITION 657 234
*$LAYER Main #
PARAMETERS 12
2           ! 1 Nb. of left-axis variables
2           ! 2 Nb. of right-axis variables
0.0         ! 3 Left axis minimum
1000        ! 4 Left axis maximum
0.0         ! 5 Right axis minimum
20000       ! 6 Right axis maximum
1           ! 7 Number of plots per simulation
12          ! 8 X-axis gridpoints
0           ! 9 Shut off Online w/o removing
43          ! 10 Logical Unit for output file
0           ! 11 Output file units
0           ! 12 Output file delimiter
INPUTS 4
BoilerkBtu        ! Equa:BoilerkBtu ->Left axis variable-1
LoadkBtu          ! Equa:LoadkBtu ->Left axis variable-2
23,1        ! Volume:Output-1 ->Right axis variable-1
23,2        ! Volume:Output-2 ->Right axis variable-2
*** INITIAL INPUT VALUES
BoilerOutput Load Return Storage
LABELS  3
```

```
"kBtu/hr"
"Storage Volume"
"Graph 1"
*** External files
ASSIGN "***.plt" 43
*|? What file should the online print to? |1000
*----------------------------------------------------------------------
--------

* Model "Temp" (Type 57)
*

UNIT 20 TYPE 57    Temp
*$UNIT_NAME Temp
*$MODEL .\Utility\Unit Conversion Routine\Type57.tmf
*$POSITION 344 223
*$LAYER Main #
PARAMETERS 6
1           ! 1 Table Nb. for input-1
1           ! 2 ID number from table for input -1
2           ! 3 ID number from table for output-1
1           ! 4 Table Nb. for input-2
1           ! 5 ID number from table for input -2
2           ! 6 ID number from table for output-2
INPUTS 2
11,1        ! Type39-2:Fluid temperature ->Input-1
12,1        ! Type39:Fluid temperature ->Input-2
*** INITIAL INPUT VALUES
0.0 0.0
*----------------------------------------------------------------------
--------

* Model "Type65c-3" (Type 65)
*

UNIT 21 TYPE 65    Type65c-3
*$UNIT_NAME Type65c-3
*$MODEL .\Output\Online Plotter\Online Plotter With File\No
Units\Type65c.tmf
*$POSITION 198 159
*$LAYER Main #
PARAMETERS 12
3           ! 1 Nb. of left-axis variables
3           ! 2 Nb. of right-axis variables
0.0         ! 3 Left axis minimum
500         ! 4 Left axis maximum
0.0         ! 5 Right axis minimum
200         ! 6 Right axis maximum
1           ! 7 Number of plots per simulation
12          ! 8 X-axis gridpoints
0           ! 9 Shut off Online w/o removing
44          ! 10 Logical Unit for output file
0           ! 11 Output file units
0           ! 12 Output file delimiter
INPUTS 6
BoilerGPM         ! Equa:BoilerGPM ->Left axis variable-1
LoadGPM           ! Equa:LoadGPM ->Left axis variable-2
```

```
12,5         ! Type39:Fluid volume ->Left axis variable-3
20,1         ! Temp:Output-1 ->Right axis variable-1
20,2         ! Temp:Output-2 ->Right axis variable-2
13,1         ! Boiler Aquastat:Output control function ->Right axis
variable-3
*** INITIAL INPUT VALUES
Boiler Load Volume Return Supply control
LABELS  3
"GPM"
"Fahrenheit"
"Graph 1"
*** External files
ASSIGN "***.plt" 44
*|? What file should the online print to? |1000
*-----------------------------------------------------------------------
--------

* Model "Type55" (Type 55)
*

UNIT 22 TYPE 55    Type55
*$UNIT_NAME Type55
*$MODEL .\Utility\Integrators\Periodic Integrator\Type55.tmf
*$POSITION 654 436
*$LAYER Main #
PARAMETERS 7
1            ! 1 Integrate or sum input
1.0          ! 2 Relative starting hour for input
1.0          ! 3 Duration for input
24.0         ! 4 Cycle repeat time for input
24           ! 5 Reset time for input
0            ! 6 Absolute starting hour for input
8760         ! 7 Absolute stopping hour for input
INPUTS 1
12,5         ! Type39:Fluid volume ->Input
*** INITIAL INPUT VALUES
0.
*-----------------------------------------------------------------------
--------

* Model "Volume" (Type 57)
*

UNIT 23 TYPE 57    Volume
*$UNIT_NAME Volume
*$MODEL .\Utility\Unit Conversion Routine\Type57.tmf
*$POSITION 771 234
*$LAYER Main #
PARAMETERS 6
4            ! 1 Table Nb. for input-1
1            ! 2 ID number from table for input -1
6            ! 3 ID number from table for output-1
4            ! 4 Table Nb. for input-2
1            ! 5 ID number from table for input -2
6            ! 6 ID number from table for output-2
INPUTS 2
11,5         ! Type39-2:Fluid volume ->Input-1
```

```
12,5        ! Type39:Fluid volume ->Input-2
*** INITIAL INPUT VALUES
0.0 0.0
*----------------------------------------------------------------------
--------

* Model "Heating Load-2" (Type 682)
*

UNIT 24 TYPE 682   Heating Load-2
*$UNIT_NAME Heating Load-2
*$MODEL .\Loads and Structures (TESS)\Flowstream Loads\Other
Fluids\Type682.tmf
*$POSITION 1081 213
*$LAYER Main #
*$# Loads to a Flow Stream
PARAMETERS 1
4.190       ! 1 Fluid Specific Heat
INPUTS 5
29,1        ! Boiler-2:Outlet Fluid Temperature ->Inlet Temperature
29,2        ! Boiler-2:Outlet Fluid Flowrate ->Inlet Flowrate
LoadNeg           ! Equa:LoadNeg ->Load
0,0         ! [unconnected] Minimum Heating Temperature
0,0         ! [unconnected] Maximum Cooling Temperature
*** INITIAL INPUT VALUES
7 10000 28799997.869134 -999 999
*----------------------------------------------------------------------
--------

* Model "Boiler-2" (Type 751)
*

UNIT 29 TYPE 751   Boiler-2
*$UNIT_NAME Boiler-2
*$MODEL .\HVAC Library (TESS)\Boiler\Efficiency from External
File\Type751.tmf
*$POSITION 1126 319
*$LAYER Main #
*$# Boiler
PARAMETERS 5
712163.069867           ! 1 Rated Capacity
4.190       ! 2 Fluid Specific Heat
45          ! 3 Logical Unit for Data File
11          ! 4 Number of Inlet Temperature Points
2           ! 5 Number of PLR's
INPUTS 4
30,1        ! Type3b-3:Outlet fluid temperature ->Inlet Fluid
Temperature
30,2        ! Type3b-3:Outlet flow rate ->Inlet Fluid Flowrate
0,0         ! [unconnected] Input Control Signal
0,0         ! [unconnected] Set Point Temperature
*** INITIAL INPUT VALUES
100.0 1000.0 1 59.999997
*** External files
ASSIGN "C:\Trnsys17\Tess Models\SampleCatalogData\Boilers\Fluid
Boiler\Efficiency.Dat" 45
```

```
*|? Which file contains the external performance data for this boiler?
|1000
*-----------------------------------------------------------------------
--------

* Model "Type3b-3" (Type 3)
*

UNIT 30 TYPE 3     Type3b-3
*$UNIT_NAME Type3b-3
*$MODEL .\Hydronics\Pumps\Variable Speed\Type3b.tmf
*$POSITION 975 319
*$LAYER Main #
PARAMETERS 5
30549.4           ! 1 Maximum flow rate
4.190       ! 2 Fluid specific heat
200         ! 3 Maximum power
0.05        ! 4 Conversion coefficient
0.5         ! 5 Power coefficient
INPUTS 3
24,1        ! Heating Load-2:Outlet Temperature ->Inlet fluid
temperature
24,2        ! Heating Load-2:Outlet Flowrate ->Inlet mass flow rate
sig         ! Equa:sig ->Control signal
*** INITIAL INPUT VALUES
20.0 100.0 1.0
*-----------------------------------------------------------------------
--------

* Model "NS" (Type 65)
*

UNIT 31 TYPE 65    NS
*$UNIT_NAME NS
*$MODEL .\Output\Online Plotter\Online Plotter With File\No
Units\Type65c.tmf
*$POSITION 1051 404
*$LAYER Main #
PARAMETERS 12
2           ! 1 Nb. of left-axis variables
2           ! 2 Nb. of right-axis variables
0.0         ! 3 Left axis minimum
1000        ! 4 Left axis maximum
0.0         ! 5 Right axis minimum
300         ! 6 Right axis maximum
1           ! 7 Number of plots per simulation
12          ! 8 X-axis gridpoints
0           ! 9 Shut off Online w/o removing
46          ! 10 Logical Unit for output file
0           ! 11 Output file units
0           ! 12 Output file delimiter
INPUTS 4
32,1        ! Cycle Integrate-2:Result of integration-1 ->Left axis
variable-1
32,2        ! Cycle Integrate-2:Result of integration-2 ->Left axis
variable-2
30,1        ! Type3b-3:Outlet fluid temperature ->Right axis variable-1
```

```
29,1        ! Boiler-2:Outlet Fluid Temperature ->Right axis variable-2
*** INITIAL INPUT VALUES
NSeu diff Return Supply
LABELS  3
"kBtu/hr"
"Storage Volume"
"Graph 1"
*** External files
ASSIGN "***.plt" 46
*|? What file should the online print to? |1000
*----------------------------------------------------------------------
--------

* Model "Cycle Integrate-2" (Type 24)
*

UNIT 32 TYPE 24    Cycle Integrate-2
*$UNIT_NAME Cycle Integrate-2
*$MODEL .\Utility\Integrators\Quantity Integrator\Type24.tmf
*$POSITION 934 506
*$LAYER Main #
PARAMETERS 2
STOP        ! 1 Integration period
0           ! 2 Relative or absolute start time
INPUTS 2
NSEUbtu           ! Equa:NSEUbtu ->Input to be integrated-1
dEU         ! Equa:dEU ->Input to be integrated-2
*** INITIAL INPUT VALUES
0.0 0.0
*----------------------------------------------------------------------
--------

END
```

## Cooling Model

```
VERSION 17
***********************************************************************
********
*** TRNSYS input file (deck) generated by TrnsysStudio
*** on Saturday, January 26, 2019 at 08:44
*** from TrnsysStudio project:
C:\Trnsys17\MyProjects\Project4\ChWFINALyear800.tpf
***
*** If you edit this file, use the File/Import TRNSYS Input File
function in
*** TrnsysStudio to update the project.
***
*** If you have problems, questions or suggestions please contact your
local
*** TRNSYS distributor or mailto:software@cstb.fr
***
```

```
************************************************************************
********

************************************************************************
********
*** Units
************************************************************************
********

************************************************************************
********
*** Control cards
************************************************************************
********
* START, STOP and STEP
CONSTANTS 3
START=0
STOP=8760
STEP=1
SIMULATION   START      STOP  STEP ! Start time      End time    Time
step
TOLERANCES 0.001 0.001              ! Integration      Convergence
LIMITS 30 1500 50                   ! Max iterations  Max warnings
      Trace limit
DFQ 1                         ! TRNSYS numerical integration solver
method
WIDTH 80                      ! TRNSYS output file width, number of
characters
LIST                          ! NOLIST statement
                              ! MAP statement
SOLVER 0 1 1                        ! Solver statement      Minimum
relaxation factor Maximum relaxation factor
NAN_CHECK 0                   ! Nan DEBUG statement
OVERWRITE_CHECK 0             ! Overwrite DEBUG statement
TIME_REPORT 0                 ! disable time report
EQSOLVER 0                    ! EQUATION SOLVER statement
* User defined CONSTANTS


* Model "Campus_Load" (Type 682)
*

UNIT 2 TYPE 682    Campus_Load
*$UNIT_NAME Campus_Load
*$MODEL .\Loads and Structures (TESS)\Flowstream Loads\Other
Fluids\Type682.tmf
*$POSITION 989 202
*$LAYER Controls #
*$# Loads to a Flow Stream
PARAMETERS 1
4.190       ! 1 Fluid Specific Heat
INPUTS 5
18,1        ! Type39:Fluid temperature ->Inlet Temperature
18,2        ! Type39:Load flow rate ->Inlet Flowrate
LoadScaled        ! Equa:LoadScaled ->Load
0,0         ! [unconnected] Minimum Heating Temperature
```

```
0,0         ! [unconnected] Maximum Cooling Temperature
*** INITIAL INPUT VALUES
7 10000 28799997.869134 -999 999
*----------------------------------------------------------------------
--------

* Model "Load" (Type 9)
*

UNIT 11 TYPE 9     Load
*$UNIT_NAME Load
*$MODEL .\Utility\Data Readers\Generic Data Files\Expert Mode\Free
Format\Type9e.tmf
*$POSITION 37 458
*$LAYER Text #
PARAMETERS 10
2           ! 1 Mode
0           ! 2 Header Lines to Skip
1           ! 3 No. of values to read
1.0         ! 4 Time interval of data
1           ! 5 Interpolate or not
3600000           ! 6 Multiplication factor
0           ! 7 Addition factor
1           ! 8 Average or instantaneous value
34          ! 9 Logical unit for input file
-1          ! 10 Free format mode
*** External files
ASSIGN "\\Wdmycloudex2\iac\IAC\Andrew V\Thesis\CoolingLoad.csv" 34
*|? Input file name |1000
*----------------------------------------------------------------------
--------

* Model "Chiller-2" (Type 666)
*

UNIT 13 TYPE 666   Chiller-2
*$UNIT_NAME Chiller-2
*$MODEL .\HVAC Library (TESS)\Chillers\Water-Cooled Chiller\Type666.tmf
*$POSITION 338 340
*$LAYER Controls #
*$# Water-Cooled Chiller
PARAMETERS 9
3257999.758946          ! 1 Rated Capacity
4.45        ! 2 Rated C.O.P.
35          ! 3 Logical Unit - Performance Data
36          ! 4 Logical Unit - PLR Data
4.190       ! 5 CHW Fluid Specific Heat
4.190       ! 6 CW Fluid Specific Heat
6           ! 7 Number of CW Points
6           ! 8 Number of CHW Points
5           ! 9 Number of PLRs
INPUTS 6
19,1        ! ChWater Pump:Outlet fluid temperature ->Chilled Water
Inlet Temperature
15,2        ! Type39-2:Load flow rate ->Chilled Water Flowrate
0,0         ! [unconnected] Cooling Water Temperature
0,0         ! [unconnected] Cooling Water Flowrate
```

```
0,0          ! [unconnected] CHW Set Point Temperature
0,0          ! [unconnected] Chiller Control Signal
*** INITIAL INPUT VALUES
12.2 100000 30.0 110000.0 6.666688 1
*** External files
ASSIGN "C:\Trnsys17\Tess
Models\SampleCatalogData\WaterCooledChiller\Samp_C.Dat" 35
*|? Which file contains the chiller performance data? |1000
ASSIGN "C:\Trnsys17\Tess
Models\SampleCatalogData\WaterCooledChiller\Samp_PLR.Dat" 36
*|? Which file contains the part-load performance data? |1000
*----------------------------------------------------------------------
--------

* EQUATIONS "Equa"
*
EQUATIONS 17
ChillerCap = 905*60*60*le([13,11],0)+[13,7]
Vmax = 25
maxload = 3513681
LoadScaled = [11,1]
maxflow = maxload/4.19/(12.22-6.6667)
loadsig = LoadScaled/maxload
md = loadsig
sigmax = ChillerCap/([19,1]-6.666688)/4.19/maxflow
mp = (sigmax-loadsig)*lt([18,9],1)
mpoon = gt(loadsig*maxflow,Vmax*1000/8)*  (loadsig*maxflow-
Vmax*1000/8)/maxflow
mc = [17,2]*(md+mp)+  (1-
[17,2])*(mpoon*le(mpoon,sigmax)+sigmax*gt(mpoon,sigmax))
+ge([15,9],1)*sigmax  +gt([15,1],17)*sigmax  +lt([23,9],Vmax-5)*(1-
[17,2])*sigmax
mc2 = le(mc,sigmax)*mc+gt(mc,sigmax)*sigmax
ChillerFlowGPM = [13,2]/3.79/60
LoadFlowGPM = [2,2]/3.79/60
dAEU = NSP-SP
NSP = [21,5]*.000278
SP = [13,5]*.000278
*$UNIT_NAME Equa
*$LAYER Main
*$POSITION 299 84

*----------------------------------------------------------------------
--------


* Model "Scheduler" (Type 9)
*

UNIT 14 TYPE 9     Scheduler
*$UNIT_NAME Scheduler
*$MODEL .\Utility\Data Readers\Generic Data Files\Expert Mode\Free
Format\Type9e.tmf
*$POSITION 62 116
*$LAYER Main #
PARAMETERS 10
3            ! 1 Mode
```

```
0            ! 2 Header Lines to Skip
1            ! 3 No. of values to read
1.0          ! 4 Time interval of data
-1           ! 5 Interpolate or not
1            ! 6 Multiplication factor
0            ! 7 Addition factor
1            ! 8 Average or instantaneous value
37           ! 9 Logical unit for input file
-1           ! 10 Free format mode
*** External files
ASSIGN "\\Wdmycloudex2\iac\IAC\Andrew
V\Thesis\ChargeScheduler11.14.csv" 37
*|? Input file name |1000
*------------------------------------------------------------------------
--------

* Model "ChWater Pump-2" (Type 3)
*

UNIT 10 TYPE 3     ChWater Pump-2
*$UNIT_NAME ChWater Pump-2
*$MODEL .\Hydronics\Pumps\Variable Speed\Type3b.tmf
*$POSITION 885 394
*$LAYER Water Loop #
PARAMETERS 5
150961             ! 1 Maximum flow rate
4.190        ! 2 Fluid specific heat
2147651.00349           ! 3 Maximum power
0            ! 4 Conversion coefficient
0            ! 5 Power coefficient
INPUTS 3
18,1         ! Type39:Fluid temperature ->Inlet fluid temperature
0,0          ! [unconnected] Inlet mass flow rate
md           ! Equa:md ->Control signal
*** INITIAL INPUT VALUES
15 150 1
*------------------------------------------------------------------------
--------

* Model "Type14h" (Type 14)
*

UNIT 17 TYPE 14    Type14h
*$UNIT_NAME Type14h
*$MODEL .\Utility\Forcing Functions\General\Type14h.tmf
*$POSITION 160 148
*$LAYER Main #
PARAMETERS 12
0            ! 1 Initial value of time
1            ! 2 Initial value of function
11.99        ! 3 Time at point
1            ! 4 Value at point
12           ! 5 Time at point
0            ! 6 Value at point
19.99        ! 7 Time at point
0            ! 8 Value at point
20           ! 9 Time at point
```

```
1            ! 10 Value at point
24           ! 11 Time at point
1            ! 12 Value at point
*-----------------------------------------------------------------------
--------

* Model "Type39" (Type 39)
*

UNIT 18 TYPE 39    Type39
*$UNIT_NAME Type39
*$MODEL .\Thermal Storage\Variable Volume Tank\Type39.tmf
*$POSITION 645 436
*$LAYER Text #
PARAMETERS 12
1            ! 1 Tank operation mode
1000         ! 2 Overall tank volume
0            ! 3 Minimum fluid volume
25           ! 4 Maximum fluid volume
15.0         ! 5 Tank circumference
4.0          ! 6 Cross-sectional area
0            ! 7 Wetted loss coefficient
0            ! 8 Dry loss coefficient
4.190        ! 9 Fluid specific heat
1000.0             ! 10 Fluid density
6.667        ! 11 Initial fluid temperature
0            ! 12 Initial fluid volume
INPUTS 4
13,1         ! Chiller-2:Chilled Water Temperature ->Inlet temperature
13,2         ! Chiller-2:Chilled Water Flowrate ->Inlet flow rate
10,2         ! ChWater Pump-2:Outlet flow rate ->Flow rate to load
0,0          ! [unconnected] Environment temperature
*** INITIAL INPUT VALUES
25.0 100.0 23000 15.0
*-----------------------------------------------------------------------
--------

* Model "Type39-2" (Type 39)
*

UNIT 15 TYPE 39    Type39-2
*$UNIT_NAME Type39-2
*$MODEL .\Thermal Storage\Variable Volume Tank\Type39.tmf
*$POSITION 604 128
*$LAYER Text #
PARAMETERS 12
1            ! 1 Tank operation mode
1000         ! 2 Overall tank volume
0            ! 3 Minimum fluid volume
25           ! 4 Maximum fluid volume
15.0         ! 5 Tank circumference
4.0          ! 6 Cross-sectional area
0            ! 7 Wetted loss coefficient
0            ! 8 Dry loss coefficient
4.190        ! 9 Fluid specific heat
1000.0             ! 10 Fluid density
12.2         ! 11 Initial fluid temperature
```

```
400         ! 12 Initial fluid volume
INPUTS 4
2,1         ! Campus_Load:Outlet Temperature ->Inlet temperature
2,2         ! Campus_Load:Outlet Flowrate ->Inlet flow rate
19,2        ! ChWater Pump:Outlet flow rate ->Flow rate to load
0,0         ! [unconnected] Environment temperature
*** INITIAL INPUT VALUES
25.0 100.0 75.0 15.0
*-----------------------------------------------------------------------
--------

* Model "ChWater Pump" (Type 3)
*

UNIT 19 TYPE 3     ChWater Pump
*$UNIT_NAME ChWater Pump
*$MODEL .\Hydronics\Pumps\Variable Speed\Type3b.tmf
*$POSITION 511 255
*$LAYER Outputs #
PARAMETERS 5
150961            ! 1 Maximum flow rate
4.190       ! 2 Fluid specific heat
26845637.543621         ! 3 Maximum power
0           ! 4 Conversion coefficient
0           ! 5 Power coefficient
INPUTS 3
15,1        ! Type39-2:Fluid temperature ->Inlet fluid temperature
0,0         ! [unconnected] Inlet mass flow rate
mc2         ! Equa:mc2 ->Control signal
*** INITIAL INPUT VALUES
15 150 1
*-----------------------------------------------------------------------
--------

* Model "Type55" (Type 55)
*

UNIT 23 TYPE 55    Type55
*$UNIT_NAME Type55
*$MODEL .\Utility\Integrators\Periodic Integrator\Type55.tmf
*$POSITION 506 42
*$LAYER Main #
PARAMETERS 7
1           ! 1 Integrate or sum input
1.0         ! 2 Relative starting hour for input
1.0         ! 3 Duration for input
24.0        ! 4 Cycle repeat time for input
24          ! 5 Reset time for input
0           ! 6 Absolute starting hour for input
8760        ! 7 Absolute stopping hour for input
INPUTS 1
18,5        ! Type39:Fluid volume ->Input
*** INITIAL INPUT VALUES
0.
*-----------------------------------------------------------------------
--------
```

```
* Model "Type24" (Type 24)
*

UNIT 20 TYPE 24    Type24
*$UNIT_NAME Type24
*$MODEL .\Utility\Integrators\Quantity Integrator\Type24.tmf
*$POSITION 101 586
*$LAYER Outputs #
PARAMETERS 2
STOP        ! 1 Integration period
0           ! 2 Relative or absolute start time
INPUTS 3
13,5        ! Chiller-2:Chiller Power ->Input to be integrated-1
21,5        ! Chiller:Chiller Power ->Input to be integrated-2
dAEU        ! Equa:dAEU ->Input to be integrated-3
*** INITIAL INPUT VALUES
0.0 0.0 0.0
*-----------------------------------------------------------------------
--------

* Model "Chiller" (Type 666)
*

UNIT 21 TYPE 666   Chiller
*$UNIT_NAME Chiller
*$MODEL .\HVAC Library (TESS)\Chillers\Water-Cooled Chiller\Type666.tmf
*$POSITION 61 266
*$LAYER Outputs #
*$# Water-Cooled Chiller
PARAMETERS 9
3517199.959495          ! 1 Rated Capacity
4.45        ! 2 Rated C.O.P.
52          ! 3 Logical Unit - Performance Data
53          ! 4 Logical Unit - PLR Data
4.190       ! 5 CHW Fluid Specific Heat
4.190       ! 6 CW Fluid Specific Heat
6           ! 7 Number of CW Points
6           ! 8 Number of CHW Points
5           ! 9 Number of PLRs
INPUTS 6
22,1        ! Campus_Load-2:Outlet Temperature ->Chilled Water Inlet
Temperature
22,2        ! Campus_Load-2:Outlet Flowrate ->Chilled Water Flowrate
0,0         ! [unconnected] Cooling Water Temperature
0,0         ! [unconnected] Cooling Water Flowrate
0,0         ! [unconnected] CHW Set Point Temperature
0,0         ! [unconnected] Chiller Control Signal
*** INITIAL INPUT VALUES
5 100000 30.0 110000.0 6.66 1
*** External files
ASSIGN "C:\Trnsys17\Tess
Models\SampleCatalogData\WaterCooledChiller\Samp_C.Dat" 52
*|? Which file contains the chiller performance data? |1000
ASSIGN "C:\Trnsys17\Tess
Models\SampleCatalogData\WaterCooledChiller\Samp_PLR.Dat" 53
*|? Which file contains the part-load performance data? |1000
```

```
*-----------------------------------------------------------------------
--------

* Model "Campus_Load-2" (Type 682)
*

UNIT 22 TYPE 682   Campus_Load-2
*$UNIT_NAME Campus_Load-2
*$MODEL .\Loads and Structures (TESS)\Flowstream Loads\Other
Fluids\Type682.tmf
*$POSITION 191 351
*$LAYER Controls #
*$# Loads to a Flow Stream
PARAMETERS 1
4.190       ! 1 Fluid Specific Heat
INPUTS 5
21,1        ! Chiller:Chilled Water Temperature ->Inlet Temperature
21,2        ! Chiller:Chilled Water Flowrate ->Inlet Flowrate
11,1        ! Load:Output 1 ->Load
0,0         ! [unconnected] Minimum Heating Temperature
0,0         ! [unconnected] Maximum Cooling Temperature
*** INITIAL INPUT VALUES
7 10000 28799997.869134 -999 999
*-----------------------------------------------------------------------
--------

* Model "Comparison" (Type 65)
*

UNIT 24 TYPE 65    Comparison
*$UNIT_NAME Comparison
*$MODEL .\Output\Online Plotter\Online Plotter With File\No
Units\Type65c.tmf
*$POSITION 364 532
*$LAYER Main #
PARAMETERS 12
4           ! 1 Nb. of left-axis variables
4           ! 2 Nb. of right-axis variables
0           ! 3 Left axis minimum
5           ! 4 Left axis maximum
0.0         ! 5 Right axis minimum
1000000           ! 6 Right axis maximum
1           ! 7 Number of plots per simulation
12          ! 8 X-axis gridpoints
0           ! 9 Shut off Online w/o removing
54          ! 10 Logical Unit for output file
0           ! 11 Output file units
0           ! 12 Output file delimiter
INPUTS 8
dAEU        ! Equa:dAEU ->Left axis variable-1
13,8        ! Chiller-2:C.O.P. ->Left axis variable-2
21,8        ! Chiller:C.O.P. ->Left axis variable-3
17,2        ! Type14h:Instantaneous value of function over the timestep
->Left axis variable-4
13,5        ! Chiller-2:Chiller Power ->Right axis variable-1
21,5        ! Chiller:Chiller Power ->Right axis variable-2
0,0         ! [unconnected] Right axis variable-3
```

```
0,0         ! [unconnected] Right axis variable-4
*** INITIAL INPUT VALUES
%AEU COPStorage COPNoStorage Scheduler SPower NSPower SPower SPower

LABELS  3
"HRS"
"KJHR"
"outputs"
*** External files
ASSIGN "chf.out" 54
*|? What file should the online print to? |1000
*----------------------------------------------------------------------
--------

* Model "Chiller Op" (Type 65)
*

UNIT 27 TYPE 65    Chiller Op
*$UNIT_NAME Chiller Op
*$MODEL .\Output\Online Plotter\Online Plotter With File\No
Units\Type65c.tmf
*$POSITION 457 351
*$LAYER Main #
PARAMETERS 12
3           ! 1 Nb. of left-axis variables
2           ! 2 Nb. of right-axis variables
0           ! 3 Left axis minimum
1.5         ! 4 Left axis maximum
0           ! 5 Right axis minimum
80          ! 6 Right axis maximum
8           ! 7 Number of plots per simulation
12          ! 8 X-axis gridpoints
0           ! 9 Shut off Online w/o removing
57          ! 10 Logical Unit for output file
0           ! 11 Output file units
0           ! 12 Output file delimiter
INPUTS 5
loadsig           ! Equa:loadsig ->Left axis variable-1
13,11             ! Chiller-2:Chiller PLR ->Left axis variable-2
18,9        ! Type39:Level indicator ->Left axis variable-3
30,2        ! Type57:Output-2 ->Right axis variable-1
30,1        ! Type57:Output-1 ->Right axis variable-2
*** INITIAL INPUT VALUES
%Load ChillerPLR StorageLevel ReturnTemp SupplyTemp
LABELS  3
""
"Temperature"
"outputs"
*** External files
ASSIGN "chwf1.out" 57
*|? What file should the online print to? |1000
*----------------------------------------------------------------------
--------

* Model "Type57" (Type 57)
*
```

```
UNIT 30 TYPE 57    Type57
*$UNIT_NAME Type57
*$MODEL .\Utility\Unit Conversion Routine\Type57.tmf
*$POSITION 517 511
*$LAYER Outputs #
PARAMETERS 6
1           ! 1 Table Nb. for input-1
1           ! 2 ID number from table for input -1
2           ! 3 ID number from table for output-1
1           ! 4 Table Nb. for input-2
1           ! 5 ID number from table for input -2
2           ! 6 ID number from table for output-2
INPUTS 2
18,3        ! Type39:Excess flow temperature ->Input-1
15,1        ! Type39-2:Fluid temperature ->Input-2
*** INITIAL INPUT VALUES
0.0 0.0
*----------------------------------------------------------------------
--------

* Model "Chiller Op-2" (Type 65)
*

UNIT 25 TYPE 65    Chiller Op-2
*$UNIT_NAME Chiller Op-2
*$MODEL .\Output\Online Plotter\Online Plotter With File\No
Units\Type65c.tmf
*$POSITION 577 276
*$LAYER Controls #
PARAMETERS 12
3           ! 1 Nb. of left-axis variables
2           ! 2 Nb. of right-axis variables
0           ! 3 Left axis minimum
900         ! 4 Left axis maximum
0           ! 5 Right axis minimum
80          ! 6 Right axis maximum
8           ! 7 Number of plots per simulation
12          ! 8 X-axis gridpoints
0           ! 9 Shut off Online w/o removing
58          ! 10 Logical Unit for output file
0           ! 11 Output file units
0           ! 12 Output file delimiter
INPUTS 5
ChillerFlowGPM          ! Equa:ChillerFlowGPM ->Left axis variable-1
LoadFlowGPM       ! Equa:LoadFlowGPM ->Left axis variable-2
18,5        ! Type39:Fluid volume ->Left axis variable-3
30,2        ! Type57:Output-2 ->Right axis variable-1
30,1        ! Type57:Output-1 ->Right axis variable-2
*** INITIAL INPUT VALUES
Chiller Load vol Return Supply
LABELS  3
"gpm"
"Temperature"
"outputs"
*** External files
ASSIGN "chwb.out" 58
*|? What file should the online print to? |1000
```

```
*----------------------------------------------------------------------
--------

* Model "Chiller Op-3" (Type 65)
*

UNIT 26 TYPE 65    Chiller Op-3
*$UNIT_NAME Chiller Op-3
*$MODEL .\Output\Online Plotter\Online Plotter With File\No
Units\Type65c.tmf
*$POSITION 446 458
*$LAYER Main #
PARAMETERS 12
3           ! 1 Nb. of left-axis variables
2           ! 2 Nb. of right-axis variables
0           ! 3 Left axis minimum
1.5         ! 4 Left axis maximum
0           ! 5 Right axis minimum
5           ! 6 Right axis maximum
8           ! 7 Number of plots per simulation
12          ! 8 X-axis gridpoints
0           ! 9 Shut off Online w/o removing
59          ! 10 Logical Unit for output file
0           ! 11 Output file units
0           ! 12 Output file delimiter
INPUTS 5
loadsig           ! Equa:loadsig ->Left axis variable-1
21,11             ! Chiller:Chiller PLR ->Left axis variable-2
21,12             ! Chiller:Fraction of Full-Load Power ->Left axis
variable-3
21,8        ! Chiller:C.O.P. ->Right axis variable-1
0,0         ! [unconnected] Right axis variable-2
*** INITIAL INPUT VALUES
%Load ChillerPLR FFLP COP SupplyTemp
LABELS  3
""
"Temperature"
"outputs"
*** External files
ASSIGN "chwf1.out" 59
*|? What file should the online print to? |1000
*----------------------------------------------------------------------
--------

* Model "Comparison-2" (Type 65)
*

UNIT 28 TYPE 65    Comparison-2
*$UNIT_NAME Comparison-2
*$MODEL .\Output\Online Plotter\Online Plotter With File\No
Units\Type65c.tmf
*$POSITION 310 607
*$LAYER Main #
PARAMETERS 12
4           ! 1 Nb. of left-axis variables
1           ! 2 Nb. of right-axis variables
-1000       ! 3 Left axis minimum
```

```
400         ! 4 Left axis maximum
-1000       ! 5 Right axis minimum
400         ! 6 Right axis maximum
1           ! 7 Number of plots per simulation
12          ! 8 X-axis gridpoints
0           ! 9 Shut off Online w/o removing
60          ! 10 Logical Unit for output file
0           ! 11 Output file units
0           ! 12 Output file delimiter
INPUTS 5
NSP         ! Equa:NSP ->Left axis variable-1
SP          ! Equa:SP ->Left axis variable-2
0,0         ! [unconnected] Left axis variable-3
0,0         ! [unconnected] Left axis variable-4
20,3        ! Type24:Result of integration-3 ->Right axis variable
*** INITIAL INPUT VALUES
nsp sp COPNoStorage Scheduler daeu
LABELS  3
"kW"
"kWh"
"outputs"
*** External files
ASSIGN "chf.out" 60
*|? What file should the online print to? |1000
*----------------------------------------------------------------------
--------

END
```

# APPENDIX B

## TRNSYS TYPE DOCUMENTATION

## 6.35. Type 751: Simple Boiler with Efficiency from Data File

Type751 models a simple steam boiler. According to ASHRAE, a boiler is defined by its overall efficiency (output/input) and by its combustion efficiency ((input energy-stack energy)/input energy). In this model, the boiler efficiency and the combustion efficiency are read from an external data file in which they are provided as a function of entering liquid temperature and device part load ratio. A version of this component exists (Type700) in which the combustion and boiler efficiency values are specified as inputs to the model instead of in an external data file.

### 6.35.1. Nomenclature

| | | |
|---|---|---|
| $Cp_{fluid}$ | [kJ/kg.K] | Specific heat of the liquid stream |
| $\dot{Q}_{need}$ | [kJ/hr] | Energy required to heat the liquid from its entering condition to the set point temperature. |
| $\dot{Q}_{max}$ | [kJ/hr] | The device capacity. The maximum rate at which energy can be delivered to the liquid. |
| $\dot{Q}_{fluid}$ | [kJ/hr] | The energy delivered to the liquid stream. |
| $\dot{Q}_{fuel}$ | [kJ/hr] | The rate at which fuel energy is consumed. |
| $\dot{Q}_{loss}$ | [kJ/hr] | The rate at which energy is lost from the device due to combustion process inefficiency. |
| $\dot{Q}_{exhaust}$ | [kJ/hr] | The rate at which energy is exhausted from the boiler through the combustion stack or chimney. |
| $\dot{m}_{fluid}$ | [kg/hr] | The mass flow rate of liquid flowing through the boiler. |
| $T_{in}$ | [ºC] | The temperature of liquid entering the boiler. |
| $T_{out}$ | [ºC] | The temperature of liquid exiting the boiler. |
| $T_{set}$ | [ºC] | The boiler set point temperature. |
| $PLR$ | [0..1] | The boiler part load ratio. |
| $\eta_{combustion}$ | [0..1] | The boiler's combustion efficiency. |
| $\eta_{boiler}$ | [0..1] | The boiler's overall efficiency. |

### 6.35.2. Mathematical Description

Type751 uses a simple efficiency equation to predict the energy requirement of heating a liquid to its set point temperature. The heater is capacity limited and in these two regards, is quite similar to standard TRNSYS Type6. Where Type751 differs from Type6 is that it reads overall device efficiency and also a combustion efficiency as functions of device part load ratio and entering liquid temperature. Type751 reports the energy lost during the combustion process and the energy exhausted from the boiler combustion stack. Type751 does not account for any phase changes in the boiler; fluid is assumed to exit from the device as a pure liquid, not as a vapor and not as a liquid vapor mixture.

### 6.35.2.1. No Flow Condition

If the flow of liquid through the Type751 boiler is zero, the model sets the output temperature equal to the input temperature and sets the output flow rate to zero. It further sets the energy transferred to the fluid, the energy lost during the combustion process, the energy exhausted through the boiler stack, the amount of fuel consumed and the device part load ratio all equal to zero. The no flow condition supersedes the device control signal meaning that if the input flow rate to the boiler is zero, the model ignores the value of the control signal. Consequently, the boiler may be ON (control signal set to 1) and yet not be meeting the requested set point temperature.

### 6.35.2.2. Boiler OFF Condition

If there is flow of liquid through the Type751 boiler but the boiler control signal is zero (OFF), the model sets the output temperature equal to the input temperature and sets the output flow rate equal to the input flow rate. As with the no flow case, Type751sets the energy transferred to the fluid, the energy lost during the combustion process, the energy exhausted through the boiler stack, the amount of fuel consumed and the device part load ratio all equal to zero.

### 6.35.2.3. Boiler ON Condition

If there is flow of liquid through the Type751 boiler and the boiler control signal is set to 1 (ON), the model first calculates the energy required to elevate the temperature of the liquid from its inlet value to the set point value the using:

$$\dot{Q}_{need} = \dot{m}_{fluid} Cp_{fluid} \left( T_{set} - T_{in} \right) \qquad \textbf{Eq. 6.35-1}$$

The required energy input is limited by the device capacity (specified as a parameter) and 0. Thus the device will not calculate a negative value of $Q_{need}$ if the inlet temperature exceeds the set point temperature and the boiler control signal is ON. If $Q_{need}$ does not exceed device capacity, the energy transferred to the liquid stream $Q_{fluid}$ is set equal to $Q_{need}$; the device is assumed to be internally controlled in such a way that it delivers only the required amount of energy to the liquid stream. The outlet temperature is set equal to the set point temperature and the part load ratio (PLR) is set according to:

$$PLR = \frac{\dot{Q}_{need}}{\dot{Q}_{max}} \qquad \textbf{Eq. 6.35-2}$$

If the boiler is capacity limited because the required energy exceeds device capacity, the energy transferred to the fluid ($Q_{fluid}$) is set to the device capacity ($Q_{max}$), the PLR is set to 1 and the outlet fluid temperature is set according to:

$$T_{out} = T_{in} + \frac{\dot{Q}_{max}}{\dot{m}_{fluid} Cp_{fluid}} \qquad \textbf{Eq. 6.35-3}$$

Once the PLR has been calculated, Type751 next queries the TRNSYS Data Reading routine with the inlet liquid temperature and the PLR value. The Data Reading routine returns values of boiler and combustion efficiency. The TRNSYS Data Reading routine is able to linearly interpolate in up to 4 dimensions of independent variables (in this case, two are provided: PLR and entering liquid temperature) but it is unable to extrapolate beyond the data range given in the external file. The value of one of the independent variables exceeds the range in the data file, the corresponding maximum or minimum value will be returned by the Data Reading routine and a warning will be printed to the TRNSYS list and simulation log files.

The Data Reading routine also expects the external data file to be in a certain format in order to read and interpolate it correctly. In the case of Type751, the first line of the data file must contain at least one value of entering liquid temperature, specified in degrees Celsius. The second line of the data file must contain at least one value of part load ratio (a value between 0 and 1). The subsequent lines of the data file must each contain two values, first a value of the combustion efficiency, then a value of the overall boiler efficiency. The boiler efficiency is defined as (output power / input power) and the combustion efficiency is defined as ((input energy-stack energy)/input energy). A sample data file has been provided in the .\Trnsys17\Tess Models\SampleCatalogData\Boilers\Fluid Boiler\ directory. The same file is reproduced at the end of this document for reference. The data is not taken from any actual device but is merely provided for syntactical reference.

Once the data reading routine returns the combustion and overall efficiency values, Type751 calculates the amount of fuel consumed by the boiler using:

$$\dot{Q}_{fuel} = \frac{\dot{Q}_{fluid}}{\eta_{boiler}} \qquad \textbf{Eq. 6.35-4}$$

The energy exhausted from the device is given by:

$$\dot{Q}_{exhaust} = \dot{Q}_{fuel}\left(1 - \eta_{combustion}\right) \qquad \textbf{Eq. 6.35-5}$$

And the energy lost during the combustion process is given by:

$$\dot{Q}_{loss} = \dot{Q}_{fuel} - \dot{Q}_{exhaust} \qquad \textbf{Eq. 6.35-6}$$

For reference, the data file for boiler efficiency data at two values of part load ratio and at eleven values of inlet liquid temperature might look like the following. Note that text appearing after the exclamation mark ( ! ) is interpreted by the TRNSYS Data Routine as a comment and is ignored.

Sample Boiler Efficiency Data

```
4.444 15.556 26.667 37.778 48.889 60.000 71.111 82.222 93.333     !INLET TEMPERATURE (C)
0.000 1.000                                                       !PART LOAD RATIO
 0.990   0.860  !combustion efficiency and boiler efficiency at 4.444, 0.000
 0.990   0.860  !combustion efficiency and boiler efficiency at 4.444, 1.000
 0.985   0.860  !combustion efficiency and boiler efficiency at 15.556, 0.000
 0.985   0.860  !combustion efficiency and boiler efficiency at 15.556, 1.000
 0.965   0.860  !combustion efficiency and boiler efficiency at 26.667, 0.000
 0.965   0.860  !combustion efficiency and boiler efficiency at 26.667, 1.000
 0.940   0.860  !combustion efficiency and boiler efficiency at 37.778, 0.000
 0.940   0.860  !combustion efficiency and boiler efficiency at 37.778, 1.000
 0.900   0.860  !combustion efficiency and boiler efficiency at 48.889, 0.000
 0.900   0.860  !combustion efficiency and boiler efficiency at 48.889, 1.000
 0.870   0.860  !combustion efficiency and boiler efficiency at 60.000, 0.000
 0.870   0.860  !combustion efficiency and boiler efficiency at 60.000, 1.000
 0.865   0.860  !combustion efficiency and boiler efficiency at 71.111, 0.000
 0.865   0.860  !combustion efficiency and boiler efficiency at 71.111, 1.000
 0.860   0.860  !combustion efficiency and boiler efficiency at 82.222, 0.000
 0.860   0.860  !combustion efficiency and boiler efficiency at 82.222, 1.000
 0.855   0.860  !combustion efficiency and boiler efficiency at 93.333, 0.000
 0.855   0.860  !combustion efficiency and boiler efficiency at 93.333, 1.000
```

## 8.2. Type 682:Heating And Cooling Loads Imposed On A Flow Stream

Often in simulating an HVAC system, the heating and cooling loads on the building have already been determined, either by measurement or through the use of another simulation program and yet the simulation task at hand is to simulate the effect of these loads upon the system. This component allows for there to be an interaction between such pre-calculated loads and the HVAC system by imposing the load upon a liquid flowing through a device. This model simply imposes a user-specified load (cooling = positive load, heating = negative load) on a flow stream and calculates the resultant outlet fluid conditions. Boiling and freezing effects are ignored so be careful when using this component. This simple model can represent any number of devices such as chillers, water-loop building loads, radiators, heat pumps etc. where the physics of the device are not important and the removal of the correct amount of energy from a flow stream IS important.

### 8.2.1. Nomenclature

| | | | |
|---|---|---|---|
| $\dot{Q}$ | - | [kJ/h] | the rate at which energy is added to or removed from the liquid stream. |
| $\dot{m}$ | - | [kg/h] | the rate at which fluid flows past the load |
| $C_p$ | - | [kJ/kg.K] | the specific heat of the liquid |
| $T_{in}$ | - | [ºC] | the temperature of liquid arriving at the load. |
| $T_{out}$ | - | [ºC] | the temperature of the liquid leaving the load. |

### 8.2.2. Detailed Description

Type682 can be thought of as an interaction point between a building load and the liquid working fluid in an HVAC system. If the interaction point is between the building and an air stream, Type693 may be used instead.

Mathematically, this model is very simple, the user provides the flow rate, specific heat, and temperature of liquid at a point in the system loop. The building loads are added to, or subtracted from that liquid, resulting in an outlet temperature just past the interaction point.

$$T_{out} = T_{in} + \frac{\dot{Q}}{\dot{m}C_p} \qquad \text{(Eq. 682.1)}$$

According to the sign convention, a positive load will result in an outlet temperature higher than the inlet temperature and vice versa; a negative load results in an outlet temperature lower than the inlet temperature.

### Example

Type682 is used in an example that can be found in:

“ . \TESS Models\Examples\Loads and Structures Library\Synthetic Building.tpf”

## 4.6.1 Type 3: Variable Speed Pump or Fan without Humidity Effects

This pump or fan model computes a mass flow rate using a variable control function, which must be between 0 and 1, and a fixed (user specified) maximum flow capacity. Pump or fan power consumption may also be calculated, either as a linear function of mass flow rate or by a user-defined relationship between mass flow rate and power consumption. With the release of TRNSYS version 14, a user-specified fraction of the pump/fan power is converted to fluid thermal energy. Due to this addition, Input files written for TRNSYS versions 13.1 and earlier that call the Type 3 subroutine will have to be modified. No modifications to TRNSYS 14 or TRNSYS 15 pump descriptions will be needed to run in TRNSYS 17.

In many systems, there is no continuous flow modulation and the control function is either 0 or 1. In this case, the outlet flow rate and the power used are either both zero or both at their maximum values.

It is imperative that the user realizes that the Type 3 routine sets the fluid flow rate for components downstream of the pump. The inlet fluid flow rate Input to the Type 3 routine is used for convergence checking only.

### 4.6.1.1 Nomenclature

| | |
|---|---|
| $C_i$ | coefficient of polynomial relating $P/P_{max}$ to $\dot{m}/\dot{m}_{max}$ |
| $C_p$ | specific heat of fluid |
| $F_{par}$ | fraction of pump/fan power converted to fluid thermal energy |
| $\dot{m}$ | pump mass flow rate |
| $\dot{m}_{max}$ | maximum flow rate (when $\gamma = 1$) |
| $P$ | power consumption of pump or fan |
| $P_{max}$ | maximum power consumption (when $\gamma = 1$) |
| $T_i$ | inlet fluid temperature |
| $T_o$ | outlet fluid temperature |
| $\gamma$ | control function ($0 \leq \gamma \leq 1$) |

### 4.6.1.2 Mathematical Description

The outlet temperature is calculated as

$$T_o = T_i + \frac{P * f_{par}}{\dot{m}\, C_p} \qquad \textbf{Eq. 4.6-1}$$

The outlet mass flow rate is simply

$$\dot{m}_o = \gamma \dot{m}_{max} \qquad \textbf{Eq. 4.6-2}$$

If only the required PARAMETERS are provided, a linear relationship between flow rate and power consumption is assumed:

$$P = \gamma P_{max} \qquad \textbf{Eq. 4.6-3}$$

If more than four PARAMETERS are provided, the additional parameters are used as coefficients in a polynomial relating power consumption to flow rate:

$$P = 0,\ T_o = T_{in} \quad \text{if } \dot{m} = 0 \qquad \text{Eq. 4.6-4}$$

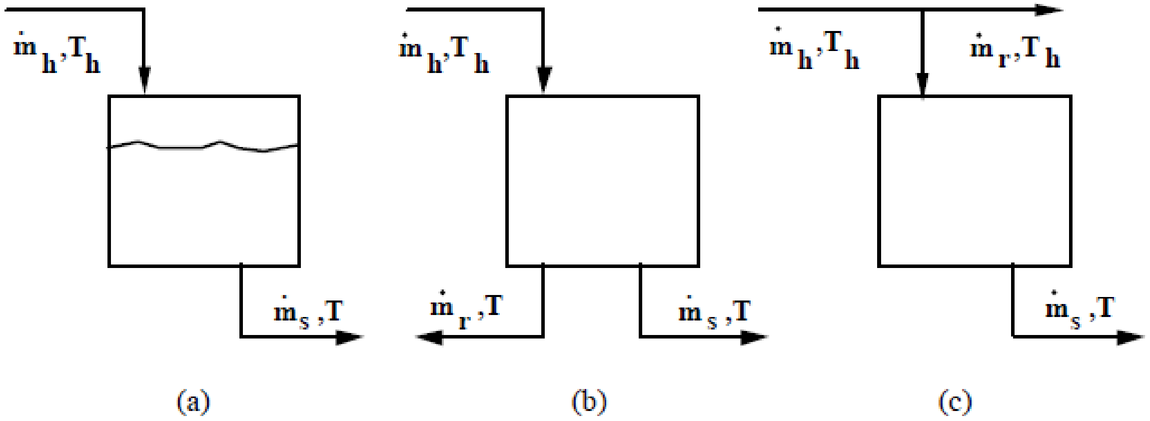
or

$$P = P_{max}\left[c_0 + c_1\gamma + c_2\gamma^2 + \dots + c_i\gamma^i\right] \text{ if } \dot{m} > 0 \qquad \text{Eq. 4.6-5}$$

where c0, cl, c2, ..., ci are entered as optional PARAMETERS 5, 6, 7, ....i+5.

## 4.12.4 *Type 39: Variable Volume Tank*

This component models a fully-mixed tank with a constant cross-sectional area that contains a variable quantity of fluid. In its simplest form, a single flow enters from a hot source and a single flow stream exits to a load as illustrated in Figure 4.12.4–1 (a). Since the incoming and outgoing flows need not be equal, the level of fluid in the tank can vary. The level is allowed to vary between user specified high and low level limits. If the lower limit is reached, the load flow necessary to maintain this level is output rather than the desired load flow. If the volume of fluid exceeds the upper limit, then the excess flow necessary to keep the tank at the upper limit is set as an output. There are two modes for handling excess flow when the upper limit is reached. In mode 1, excess flow mixes with the contents of the tank to simulate a recirculation flow stream as illustrated in Figure 4.12.4–1 (b). In this case, the temperature of the excess flow stream is the temperature of the contents of the tank. In mode 2, the excess incoming fluid stream is diverted from the tank as illustrated in Figure 4.12.4–1 (c). The temperature of the diverted stream is equal to that of the incoming flow stream.



(a) (b) (c)

**Figure 4.12.4–1: Variable Volume Tank Configurations**

### 4.12.4.1 *Nomenclature*

| | |
|---|---|
| $A_x$ | cross-sectional area of tank |
| $C_{pf}$ | specific heat of fluid in tank |
| $C_x$ | circumference of tank |
| $\dot{m}_h$ | flow rate of incoming hot stream |
| $\dot{m}_i$ | net incoming flow rate; $\dot{m}_h$ in mode 1; $\dot{m}_h - \dot{m}_r$ in mode 2 |
| $\dot{m}_L$ | flow rate required by load |
| $\dot{m}_o$ | net flow leaving tank; $\dot{m}_s - \dot{m}_r$ in mode 1; $\dot{m}_s$ in mode 2 |
| $\dot{m}_r$ | flow rate of recirculation or diverted stream necessary to keep fluid level at the upper limit |
| $\dot{m}_s$ | actual flow rate supplied to load |
| $M$ | instantaneous mass of fluid in tank |
| $\overline{M}$ | average mass of fluid in tank over the timestep |
| $M_I$ | initial mass of fluid in tank |
| $M_\tau$ | mass of fluid in tank at end of timestep |
| $M_{\tau-\Delta t}$ | mass of fluid in tank at beginning of timestep |

| | |
|---|---|
| $\dot{Q}_{env}$ | energy loss rate from tank to environment |
| $t$ | time |
| $T$ | instantaneous temperature of fluid in tank |
| $\overline{T}$ | average fluid temperature in tank over timestep |
| $T_{env}$ | environmental temperature for losses from tank |
| $T_h$ | temperature of incoming hot flow stream |
| $T_I$ | initial temperature of fluid in tank |
| $T_\tau$ | temperature of fluid at end of timestep |
| $T_{\tau\text{-}\Delta t}$ | temperature of fluid at beginning of timestep |
| $U_d$ | loss coefficient for dry portion of tank |
| $U_w$ | loss coefficient for wetted portion of tank |
| $(UA)_t$ | overall conductance for heat loss from tank |
| $V_I$ | initial volume of fluid in tank |
| $\overline{V}$ | average volume of fluid over timestep |
| $V_{min}$ | minimum allowable volume of fluid in tank |
| $V_{max}$ | maximum allowable volume of fluid in tank |
| $V$ | volume of tank |
| $\Delta E$ | change in internal energy of fluid in the tank since the beginning of the simulation |
| $\Delta\dot{H}$ | difference between the enthalpies of the outgoing and incoming flowstream per unit time |
| $\Delta t$ | simulation timestep |
| $\rho_f$ | fluid density |

### 4.12.4.2 Mathematical Description

The variable volume tank is modeled as a fully-mixed variable mass of water. The two differential equations describing the rate of change of mass and internal energy are:

$$\frac{dM}{dt} = \dot{m}_i - \dot{m}_o \qquad \text{(Eq 5.12.4.1)}$$

$$C_{pf}\frac{d(MT)}{dt} = \dot{m}_i C_p T_h - \dot{m}_o C_p T - (UA)_t(T - T_{env}) \qquad \text{(Eq 5.12.4.2)}$$

The net flow into the tank, $\dot{m}_1$, is $\dot{m}_h$ in Mode 1 and $\dot{m}_h - \dot{m}_r$ in Mode 2. The net flow leaving the tank is $\dot{m}_s - \dot{m}_r$ in Mode 1 and $\dot{m}_s$ in Mode 2.

The solutions of (Eq 5.12.4.1) for the final and average mass for a given timestep are:

$$M_\tau = M_{\tau\text{-}\Delta t} + (\dot{m}_i - \dot{m}_o)\Delta t \qquad \text{(Eq 5.12.4.3)}$$

$$\overline{M} = \frac{M_\tau + M_{\tau\text{-}\Delta t}}{2} \qquad \text{(Eq 5.12.4.4)}$$

Simultaneous solution of (Eq 5.12.4.1) and (Eq 5.12.4.2) for final and average fluid temperatures for a timestep gives

$$T_\tau = \frac{a}{b} + \left(T_{\tau-\Delta t} - \frac{a}{b}\right)\left(1 + \frac{c\Delta t}{M_{\tau-\Delta t}}\right)^{-b/c} \qquad \text{(Eq 5.12.4.5)}$$

$$\overline{T} = \frac{a}{b} + \frac{M_{\tau-\Delta t}\left(T_{\tau-\Delta t} - \frac{a}{b}\right)}{(c - b)\Delta t}\left(\left(1 + \frac{C\Delta t}{M_{\tau-\Delta t}}\right)^{(1-b/c)} - 1\right) \quad \text{(Eq 5.12.4.6)}$$

where,

$$a = \dot{m}_i T_h + \frac{(UA)_t}{C_{pf}} T_{env}$$

$$b = \dot{m}_i + \frac{(UA)_t}{C_{pf}}$$

$$c = \dot{m}_i - \dot{m}_o$$

For the situation where the incoming flow equals the total outgoing flow (i.e. no net change in mass), the following differential equation results:

$$M_{\tau-\Delta t}\frac{dT}{dt} = \dot{m}_i(T_h - T) - \frac{(UA)_t}{C_{pf}}(T - T_{env}) \quad \text{(Eq 5.12.4.7)}$$

This equation is solved analytically.

The change internal energy, the difference in enthalpies per unit time between outgoing and incoming flow streams, and energy loss rate are calculated as:

$$\Delta E = C_{pf} \cdot \left(M_\tau T_\tau - M_I T_I\right) \quad \text{(Eq 5.12.4.8)}$$

$$\Delta \dot{H} = \dot{m}_i C_{pf} T_h - \dot{m}_o C_{pf} \overline{T} \quad \text{(Eq 5.12.4.9)}$$

$$\dot{Q}_{env} = (UA)_t\left(\overline{T} - T_{env}\right) \quad \text{(Eq 5.12.4.10)}$$

The overall conductance for heat loss from the tank, $(UA)_t$, is calculated based upon average wetted and dry areas for the current timestep and user specified wet and dry loss coefficients.

## 4.1.1. Type 2: Differential Controller

This controller generates a control function $\gamma_o$ that can have values of 0 or 1. The value of $\gamma_o$ is chosen as a function of the difference between upper and lower temperatures, $T_H$ and $T_L$, compared with two dead band temperature differences, $\Delta T_H$ and $\Delta T_L$. The new value of $\gamma_0$ is dependent on whether $\gamma_i = 0$ or 1. The controller is normally used with $\gamma_0$ connected to $\gamma_i$ giving a hysteresis effect. For safety considerations, a high limit cut-out is included with the TYPE 2 controller. Regardless of the dead band conditions, the control function will be set to zero if the high limit condition is exceeded. Note that this controller is not restricted to sensing temperatures, even though temperature notation is used throughout the documentation.

### 4.1.1.1. Nomenclature

| | | |
|---|---|---|
| $\Delta T_H$ | [C] | upper dead band temperature difference |
| $\Delta T_L$ | [C] | lower dead band temperature difference |
| $T_H$ | [C] | upper Input temperature |
| $T_{IN}$ | [C] | temperature for high limit monitoring |
| $T_L$ | [C] | lower Input temperature |
| $T_{MAX}$ | [C] | maximum Input temperature |
| $\gamma_I$ | [0..1] | Input control function |
| $\gamma_O$ | [0..1] | output control function |

### 4.1.1.2. Mathematical Description

Mathematically, the control function is expressed as follows:

*IF THE CONTROLLER WAS PREVIOUSLY ON*

If $\gamma_i = 1$ and $\Delta T_L \le (T_H - T_L)$, $\gamma_O = 1$ **Eq. 4.1-1**

If $\gamma\iota = 1$ and $\Delta T_L > (T_H - T_L)$, $\gamma_O = 0$ **Eq. 4.1-2**

*IF THE CONTROLLER WAS PREVIOUSLY OFF*

If $\gamma_i = 0$ and $\Delta T_H \le (T_H - T_L)$, $\gamma_O = 1$ **Eq. 4.1-3**

If $\gamma_i = 0$ and $\Delta T_H > (T_H - T_L)$, $\gamma_O = 0$ **Eq. 4.1-4**

However, the control function is set to zero, regardless of the upper and lower dead band conditions, if $T_{IN} > T_{MAX}$. This situation is often encountered in domestic hot water systems where the pump is not allowed to run if the tank temperature is above some prescribed limit.

The controller function is shown graphically as follows.

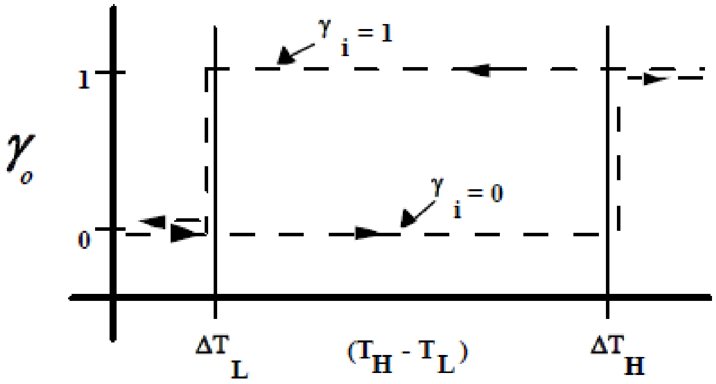


**Figure 4.1.1–1: Controller Function**

### 4.1.1.3. *Special considerations*

#### **TYPE 2 INTERACTION WITH THE TRNSYS SOLVER**

With the default TRNSYS solver (SOLVER 0, successive substitution), when ($T_H$-$T_L$) nears the upper or lower dead band in the normal mode of operation, $\gamma_0$ may sometimes oscillate between 1 and 0 for successive iterations at a given time step. This happens because $T_H$ and $T_L$ change slightly during each iteration, alternately satisfying and not satisfying the conditions for switching the controller. The value of PARAMETER 1, NSTK, is the number of oscillations permitted within a time step before the control function, $\gamma_0$, ceases to change. In general, it is recommended that NSTK be set to an odd number, typically five in order to encourage the controller to come to rest at a state different than at the previous time step.

With the release of TRNSYS version 14.1, an additional controller mode was added for use with the Powell's Method Solver. The Powell's Method control strategy is more robust in certain situations than the previous control strategy, solving the system of equations by not permitting the control variable to change during the iteration process. Upon convergence, the controller state is compared to the desired controller state at the converged solution and the calculations repeated if necessary. Please refer to section 4.1 of this document and see Volume 07 – "TRNEdit: Editing the Input File and Creating TRNSED Applications" for more information on the Powell's Method control strategy. It is important to note that if you use the Powell's Method control strategy, you must also use SOLVER 1 in your system.

For most simulations, use of the two control strategies will yield similar results. However, in short term simulations with unstable control behavior, the Successive Substitution (SOLVER 0) control strategy with an odd value of NSTK may yield quite different results from the Powell's Method control strategy.

## 4.13.5 Type 55: Periodic integrator

During a transient simulation, it is often desirable to know some basic statistics of an INPUT over a specified time range. This component calculates the count, mean, sample standard deviation, sum of squares, variance, minimum, time at which the minimum occurs, maximum, and time at which the maximum occurs of up to ten Inputs over a range of time periods specified by the user. In addition, the component will calculate the integral of the Input with respect to time or alternatively, the sum of the Input over the specified time range. This component has no physical counterpart in actual hardware but is included in the information flow diagram like any other component.

What makes this component especially useful is its ability to perform periodic summaries over a large number of user-specified time ranges. For example, with this component it is possible to determine the mean monthly value of solar radiation on a tilted surface from 8:00 a.m. to 9:00 a.m. Another example where this component would provide useful might be the determination of the annual compressor power used by a refrigeration system from 5:00 p.m. Friday to midnight Sunday.

For each Input (up to 10), the user must specify whether the Input should be integrated or summed, the starting time of the day for the periodic summary, the length of time for each period of the summary, the repeat time between summary periods, the reset time of the summary, and the absolute start and stop times for the summary.

### 4.13.5.1 Nomenclature

| | |
|---|---|
| Lengthi | duration of period for Input i (hours) |
| Maxi | maximum value of Input i over the time range |
| Meani | mean value of Input i |
| Mini | minimum value of Input i over the time range |
| Ni | number of values of Input i per reset time |
| Repeati | time interval between periods for Input i (hours) |
| Reseti | time interval over which Input i should be investigated (hours) |
| Starti | absolute starting time for summary of Input i (hour of year) |
| SSDi | sample standard deviation of Input i |
| SSQi | sum of squares of Input i |
| Stopi | absolute stopping time for summary of Input i (hour of year) |
| Toni | relative starting hour of period for each summary of Input i |
| VALi | variable taking either the value of the Input or 0 |
| Vari | variance of Input i over time period of interest |
| Yi | integral or sum of Input i over time period of interest |
| $\Delta t$ | simulation timestep |

### 4.13.5.2 Mathematical Description

The user has the option of specifying whether Input i should be integrated or summed over the periods of interest. If the Input is to be integrated, the following formulation applies:

$$Y_i = \int_{Start_i}^{Stop_i} VAL_i \; dt$$ **Eq 4.13.5-1**

If instead the Input is to be summed over the periods of interest:

$$Y_i = \sum_{Start_i}^{Stop_i} VAL_i$$ **Eq 4.13.5-2**

where:

$VAL_i = INPUT_i$ if $[Ton_i + n\ (Repeat_i)] \le TIME \le [Ton_i + length_i\ n\ (Repeat_i)]$ n = 0,1,2,3…
$VAL_i = 0$ otherwise

The total number of values of Input i to be evaluated per reset time is defined as the count of Input i. For the periodic integrator, the count of Input i may be expressed as:

$$N_i = \left(\frac{Length_i\ (hrs)}{\Delta t\ (hrs)}\right)\left(\frac{Reset_i\ (hrs)}{Repeat_i\ (hrs)}\right)$$ **Eq 4.13.5-3**

The mean value of Input i is defined as the average value of Input i over the period of interest.

$$Mean_i = \frac{\sum_{Start_i}^{Stop_i} VAL_i}{N_i}$$ **Eq 4.13.5-4**

To determine how the Inputs of i deviate from the mean value of Input i, the standard deviation of Input i is calculated. The standard deviation of Input i is a measure of the degree to which the values of Input i vary from the average value of Input i. The lower the standard deviation, the closer the values of Input i are grouped around the mean.

The periodic integrator calculates the <u>sample</u> standard deviation (SSD) of Input i over the time period.

$$SSD_i = \sqrt{\frac{\sum_{Start_i}^{Stop_i} (VAL_i - Mean_i)^2}{N_i - 1}}$$ **Eq 4.13.5-5**

Another measure of the degree to which Input i is grouped around the mean value of Input i is the variance. The variance is the summation of the squares of the difference between Input i and the mean value of Input i. Similar to the standard deviation, the lower the variance, the less the individual values of Input i vary from the mean. A lower value of variance also implies that the mean is a more reliable estimate of the entire sample.

$$VAR_i = \frac{\sum_{Start_i}^{Stop_i} (VAL_i - Mean_i)^2}{N_i - 1}$$ **Eq 4.13.5-6**

Note: The variance is simply the square of the sample standard deviation.

The summation of the squares of Input i, another measure of the deviation of Input i from its mean, is also kept by the periodic integrator and defined as:

$$\mathrm{SSQ}_i = \sum_{\mathrm{Start}_i}^{\mathrm{Stop}_i} (\mathrm{VAL}_i - \mathrm{Mean}_i)^2 \qquad \textbf{Eq 4.13.5-7}$$

### 4.13.5.3 Special Considerations

Up to 10 Inputs may be specified for the summary.

The required number of Parameters is equal to the number of Inputs supplied multiplied by seven.

The number of Outputs is equal to the number of Inputs multiplied by ten.

Outputs 1,11,21.... are either the integral of Input i with respect to time, or the summation of Input i over the specified time range. Care must be taken to choose the correct method of evaluating the Input.

# 6.17. Type 666: Water Cooled Chiller

Type666 models a vapor compression style water cooled chiller. It relies on catalog data provided as external text files to determine chiller performance. Example data files and information on data file format are provided.

## 6.17.1. Nomenclature

| | | |
|---|---|---|
| $COP_{nom}$ | [ - ] | Chiller nominal Coefficient of Performance at current conditions. |
| $COP_{rated}$ | [ - ] | Chiller rated Coefficient of Performance at current conditions. |
| $COP_{ratio}$ | [ - ] | Chiller COP at current conditions divided by the rated COP. |
| $Capacity$ | [kJ/hr] | Chiller capacity at current conditions. |
| $Capacity_{rated}$ | [kJ/hr] | Chiller rated capacity. |
| $Capacity_{ratio}$ | [kJ/hr] | Chiller capacity at current conditions divided by the rated capacity. |
| $\dot{Q}_{load}$ | [kJ/hr] | Current load on the chiller. |
| $\dot{Q}_{met}$ | [kJ/hr] | Load met by the chiller. |
| $\dot{Q}_{rejected}$ | [kJ/hr] | Energy rejected by the chiller to the ambient. |
| $\dot{m}_{chw}$ | [kg/hr] | Flow rate of fluid entering the chilled fluid stream. |
| $Cp_{chw}$ | [kJ/kg.K] | Specific heat of fluid entering the chilled fluid stream. |
| $\dot{m}_{cw}$ | [kg/hr] | Flow rate of fluid entering the cooling fluid stream. |
| $Cp_{cw}$ | [kJ/kg.K] | Specific heat of fluid entering the cooling fluid stream. |
| $T_{chw,set}$ | [ºC] | Desired outlet temperature of fluid in the chilled fluid stream. |
| $T_{chw,in}$ | [ºC] | Temperature of fluid entering the chilled fluid stream. |
| $T_{chw,out}$ | [ºC] | Temperature of fluid exiting the chilled fluid stream. |
| $PLR$ | [0..1] | Chiller Part Load Ratio (the ratio of the current load to the rated load). |
| $P$ | [kJ/hr] | Power drawn by the chiller at current conditions. |
| $FFLP$ | [0..1] | Fraction of full load power. |

## 6.17.2. Mathematical Description

Type666 relies on a catalog data lookup method to predict the performance of a vapor compression style water cooled chiller. These devices cool a fluid stream on the evaporator side while rejecting heat to a second fluid stream on the condenser side. The fluid stream being cooled is referred to as the chilled water stream while the stream to which energy is rejected is referred to as the cooling fluid stream. Because of the data lookup approach, this component may be equally well used to model single and multi stage chillers. To set up the model, the user must provide two text based data files in the standard TRNSYS data file format. The first of these files provides the chiller's capacity ratio (dimensionless) and the chiller's COP ratio (dimensionless) for varying values of chilled water set point temperature (in ºC), and for varying entering cooling water temperatures (in ºC). The second data file provides values of the chiller's fraction of full load power for varying values of part load ratio. A schematic diagram showing a single stage water cooled chiller is shown in Figure 6.17-1.

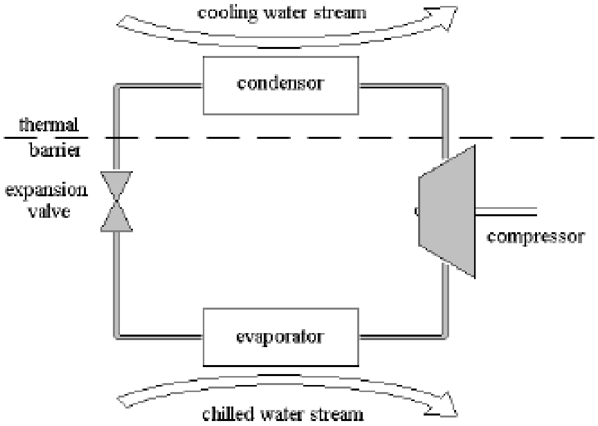


**Figure 6.17-1: Schematic Diagram of a Single Stage Water Cooled Chiller**

At a given time step, Type666 first performs a call to the TRNSYS DynamicData routine with the current cooling water (sink) temperature and the chilled water set point temperature, obtaining in return the COP ratio and capacity ratio for those conditions. The chiller's nominal COP is calculated using Equation 666.1 and the capacity at current conditions is calculated using Equation 666.2. The implicit assumption in the first call to DynamicData is that the chiller is running at full load.

$$COP_{nom} = COP_{rated} * COP_{ratio}$$ **Eq. 6.17-1**

$$Capacity = Capacity_{rated} * Capacity_{ratio}$$ **Eq. 6.17-2**

The chiller load is calculated by

$$\dot{Q}_{load} = \dot{m}_{chw} * Cp_{chw}\left(T_{chw,in} - T_{chw,set}\right)$$ **Eq. 6.17-3**

The PLR (part load ratio) is therefore

$$PLR = \frac{\dot{Q}_{load}}{Capacity}$$ **Eq. 6.17-4**

If the calculated PLR is greater than unity, Type666 automatically limits the load met by the chiller to the capacity of the machine. With a valid PLR calculated (between 0 and 1), the DynamicData routine is called again, this time specifying the second data file. The resulting value is the fraction of full load capacity for the current conditions. The chiller's power draw is given by

$$P = \frac{Capacity}{COP_{nom}} FFLP$$ **Eq. 6.17-5**

A corrected COP is then calculated as

$$COP = \frac{\dot{Q}_{met}}{P}$$ **Eq. 6.17-6**

The energy rejected to the cooling fluid stream by the device is therefore

$$\dot{Q}_{rejected} = \dot{Q}_{met} + P$$ **Eq. 6.17-7**

and the outlet temperature of the chilled fluid stream is

$$T_{chw,out} = T_{chw,in} - \frac{\dot{Q}_{met}}{\dot{m}_{chw} Cp_{chw}}$$ **Eq. 6.17-8**

while the outlet temperature of the cooling fluid stream is

$$T_{chw,out} = T_{cw,in} - \frac{\dot{Q}_{rejectedt}}{\dot{m}_{cw} Cp_{cw}}$$ **Eq. 6.17-9**

Example data files are provided in the Catalog_Data\WCCs\Sample directory. The format of the data files is shown below for reference.

Example Capacity Ratio and COP Ratio Data File

```
5       6       7        8       9       10    !Chilled water leaving temperature (C)
16      20      25       30      35      40    !Cooling water inlet temperature (C)
1.0403   1.3348      !Capacity ratio and COP ratio at 5 C outlet CHWT and 16 C inlet CWT
1.0161   1.1843      !Capacity ratio and COP ratio at 5 C outlet CHWT and 20 C inlet CWT
0.9859   1.0742      !Capacity ratio and COP ratio at 5 C outlet CHWT and 25 C inlet CWT
0.9556   0.9596      !Capacity ratio and COP ratio at 5 C outlet CHWT and 30 C inlet CWT
0.9253   0.8629      !Capacity ratio and COP ratio at 5 C outlet CHWT and 35 C inlet CWT
0.8951   0.7775      !Capacity ratio and COP ratio at 5 C outlet CHWT and 40 C inlet CWT
1.0623   1.3573      !Capacity ratio and COP ratio at 6 C outlet CHWT and 16 C inlet CWT
1.0381   1.2292      !Capacity ratio and COP ratio at 6 C outlet CHWT and 20 C inlet CWT
1.0081   1.0944      !Capacity ratio and COP ratio at 6 C outlet CHWT and 25 C inlet CWT
0.9778   0.9798      !Capacity ratio and COP ratio at 6 C outlet CHWT and 30 C inlet CWT
0.9475   0.8809      !Capacity ratio and COP ratio at 6 C outlet CHWT and 35 C inlet CWT
0.9175   0.7978      !Capacity ratio and COP ratio at 6 C outlet CHWT and 40 C inlet CWT
1.0843   1.3820      !Capacity ratio and COP ratio at 7 C outlet CHWT and 16 C inlet CWT
1.0601   1.2517      !Capacity ratio and COP ratio at 7 C outlet CHWT and 20 C inlet CWT
1.0301   1.1169      !Capacity ratio and COP ratio at 7 C outlet CHWT and 25 C inlet CWT
1.0000   1.0000      !Capacity ratio and COP ratio at 7 C outlet CHWT and 30 C inlet CWT
0.9699   0.9011      !Capacity ratio and COP ratio at 7 C outlet CHWT and 35 C inlet CWT
0.9397   0.8157      !Capacity ratio and COP ratio at 7 C outlet CHWT and 40 C inlet CWT
1.1061   1.4045      !Capacity ratio and COP ratio at 8 C outlet CHWT and 16 C inlet CWT
1.0821   1.2742      !Capacity ratio and COP ratio at 8 C outlet CHWT and 20 C inlet CWT
1.0521   1.1371      !Capacity ratio and COP ratio at 8 C outlet CHWT and 25 C inlet CWT
1.0222   1.0202      !Capacity ratio and COP ratio at 8 C outlet CHWT and 30 C inlet CWT
0.9921   0.9191      !Capacity ratio and COP ratio at 8 C outlet CHWT and 35 C inlet CWT
0.9621   0.8337      !Capacity ratio and COP ratio at 8 C outlet CHWT and 40 C inlet CWT
1.1281   1.4270      !Capacity ratio and COP ratio at 9 C outlet CHWT and 16 C inlet CWT
1.1041   1.2966      !Capacity ratio and COP ratio at 9 C outlet CHWT and 20 C inlet CWT
1.0743   1.1573      !Capacity ratio and COP ratio at 9 C outlet CHWT and 25 C inlet CWT
```

```
1.0444   1.0404      !Capacity ratio and COP ratio at 9 C outlet CHWT and 30 C inlet CWT
1.0143   0.9393      !Capacity ratio and COP ratio at 9 C outlet CHWT and 35 C inlet CWT
0.9845   0.8517      !Capacity ratio and COP ratio at 9 C outlet CHWT and 40 C inlet CWT
1.1501   1.4494      !Capacity ratio and COP ratio at 10 C outlet CHWT and 16 C inlet CWT
1.1261   1.3191 !Capacity ratio and COP ratio at 10 C outlet CHWT and 20 C inlet CWT
1.0963   1.1798 !Capacity ratio and COP ratio at 10 C outlet CHWT and 25 C inlet CWT
1.0666   1.0607 !Capacity ratio and COP ratio at 10 C outlet CHWT and 30 C inlet CWT
1.0367   0.9573 !Capacity ratio and COP ratio at 10 C outlet CHWT and 35 C inlet CWT
1.0069   0.8697 !Capacity ratio and COP ratio at 10 C outlet CHWT and 40 C inlet CWT
```

Example PLR Data File

```
0.0  0.25  0.50  0.75  1.00                        ! Part Load Ratio
0.0000                                 ! Fraction of Full Load Power at PLR=0.00
0.2497                                 ! Fraction of Full Load Power at PLR=0.25
0.4956                                 ! Fraction of Full Load Power at PLR=0.50
0.6902                                 ! Fraction of Full Load Power at PLR=0.75
1.0000                                 ! Fraction of Full Load Power at PLR=1.00
```

## 4.13.2 Type14: Time Dependent Forcing Function

In a transient simulation, it is sometimes convenient to employ a time-dependent forcing function which has a behavior characterized by a repeated pattern. The purpose of this routine is to provide a means of generating a forcing function of this type. The pattern of the forcing function is established by a set of discrete data points indicating its values at various times through one cycle. Linear interpolation is provided in order to generate a continuous forcing function from this discrete data.

### 4.13.2.1 Nomenclature

| | |
|---|---|
| TIME | current value of time in simulation |
| $C_T$ | the cycle time (the time span after which the pattern repeats itself, which may be the total simulation time) |
| N | the number of segments defining the function (N+1 points must be specified) |
| $V_o$ | the initial value of the forcing function (occurs at TIME = 0, CT, 2CT, 3CT etc.) |
| $V_i$ | the value of the forcing function at point i |
| $t_i$ | the elapsed time from the start of the cycle at which point i and Vi are reached |
| $\overline{V}$ | the linearly interpolated average value of the function over the timestep |
| $t_o$ | the initial value of time. Must be zero if the function repeats itself. IF CT is the total simulation time, $t_o$ can be less than or equal to the initial simulation time |
| $\Delta t$ | the simulation timestep |

### 4.13.2.2 Mathematical Description

The cycle must be completely specified requiring that $t_N$ ($t_N = t_i$ at i = $_N$) be greater than or equal to $C_T$.

$\overline{V}$, the average value of the function, is calculated as follows:

$$t_c = \mathrm{MOD}\,(\mathrm{TIME}, C_T) - \Delta t/2 \qquad \textbf{Eq 4.13.2-1}$$

i is then found satisfying $t_{i-1} < t_c < t_i$ then

$$R = \frac{t_c - t_{i-1}}{t_i - t_{i-1}} \qquad \textbf{Eq 4.13.2-2}$$

$$\overline{V} = V_{i-1} + R\left(V_i - V_{i-1}\right) \qquad \textbf{Eq 4.13.2-3}$$

### 4.13.2.3 Special considerations

Both the instantaneous value of the forcing function are available as outputs. When step-like functions are to be defined, it is recommended to define the function by repeating each time value with two different values of V, and then use the average value (output(1)) in the simulation. This will guarantee the use of the exact same profile for any value of the time step.

E.g. to define an occupancy in a building between  8 AM and 5PM (occupancy is 0 at night, 1 during the day, and must change instantly from 0 to 1 and 1 to 0):

- Define the origin (time = 0, V = 0)
- Define the time at which the occupancy starts, repeating the value 0 (time = 8, V = 0)
- Repeat the time at which the occupancy stops with the value 1 (time = 8, V = 1)
- Define the time at which the occupancy stops, repeating the value 1 (time = 17, V = 1)
- Repeat the time at which the occupancy stops with the value 1 (time = 17, V = 0)
- Define the end of the period $t_c$ (after that the cycle is repeated) (time = 24, V = 0)
- Use output(1) (average value over the time step)

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