A SOLAR THERMAL SYSTEM WITH SEASONAL STORAGE FOR A NET-ZERO ENERGY SCHOOL

By

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DEFINITION OF TERMS

Absorber. The component of a solar thermal collector that receives solar radiation and converts it to thermal energy.

Active solar system. A solar thermal system that relies on a method for circulating heat transfer fluid through the system other than the buoyancy forces caused by temperature gradients within the system itself.

Adaptive solar design. A building design with integrated solar elements. Additionally, the building has a form that maximizes the use of the solar resource, like facades angled to increase the incident radiation.

Additive solar design. A solar system installed in or on the building it supplies power to that does not serve an aesthetic, structural or other purpose beyond generating energy.

Borehole thermal energy storage (BTES). A system for storing thermal energy in the ground by circulating a heat transfer fluid through cylindrical vertical holes drilled in the ground. (Breger, Hubbell, Hasnaoui, & Sunderland, 1996)

Building area to volume ratio. The ratio of the surface area of a building to the volume of conditioned space of the building.

Building envelope. The portion of a building that forms the boundary between external conditions and the controlled conditions inside the building.

Building Load Analysis and System Thermodynamics (BLAST). A software tool developed to assist architects and engineers in assessing building demands for energy and predict the performance of buiding mechanical systems.

Closed loop. A conduit for moving a heat transfer fluid that forms a closed path and does not lose or gain fluid. In solar thermal systems closed loops are differentiated from open loops by the absence of mixing of the fluid contained within the closed loop with any other fluids in the system.

Collector absorption coefficient ($F_R(\tau\alpha)_n$). A parameter describing how a solar thermal collector absorbs incident solar radiation. Values can be found through testing or detailed calculations. Test values for many collectors are are available from the Solar Ratings and Certification Corporation.

Collector azimuth (γ). The "deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, with zero due south, east negative, and west positive" (Duffie & Beckman, 2006)

Collector efficiency (η). The fraction of the radiative energy incident on the exterior surface of a solar collector that is converted to usable thermal energy.

Collector loss coefficient ($F_R U_L$). A parameter describing the rate of heat loss from a solar thermal collector. Values can be found through testing or detailed calculations. Test values for many collectors are available from the Solar Ratings and Certification Corporation.

Collector slope (β). The "angle between the plane of the surface in question and the horizontal" (Duffie & Beckman, 2006)

Commercial building energy use. Energy that is used by buildings occupied by businesses, government organizations, and institutional living quarters. (U.S. Department of Energy, 2008)

Critical radiation level. A value of radiation incident on a solar thermal collector that is only great enough so that the radiation absorbed equals the thermal losses for a given collector heat loss coefficient, collector temperature, and ambient temperature.

Density (ρ). The mass of a material that is contained within a given volume. The units are in the SI system are kg/m^3.

Differential controller. An electronic control that provides or denies electrical power based on a comparison of two input values. Differential controllers used in solar thermal systems typically compare the temperature of fluid leaving the collectors to the temperature of the fluid near the bottom of the thermal storage to turn on or off a fan or pump circulating the heat transfer fluid.

Drainback system. A solar thermal system that incorporates a small reservoir to hold the volume of fluid contained in the collectors when the heat transfer fluid is not being circulated. Draining the heat transfer fluid from the collectors prevents freezing and overheating of heat transfer fluid in the collector.

EnergyPlus. A software for simulating the performance of building systems and calculating building energy demands based on the Building Load Analysis and System Thermodynamics and DOE-2 software. It was developed by the Lawrence Berkley National Laboratory (U.S. Department of Energy, 2010d).

Grid-tied photovoltaic system. A solar system that produces electricity through the photovoltaic effect that is connected to the electric grid. These systems can feed energy into the electric grid when they are producing more electricity than the building they are connected to is consuming.

Heat transfer fluid (HTF). A material used to move heat between physical locations, typically in conjunction with a heat exchanger. The material is typically non-reactive, has a high heat capacity, and low viscosity.

Incidence angle modifier ($K_{\tau\alpha}$). A parameter that accounts for the variation in reflection of solar radiation incident on a solar thermal collector due to changes in the angle between the solar radiation and a perpendicular to the collector surface.

Industry energy use. Energy "of all facilities and equipment used for producing, processing, or assembling goods". (U.S. Department of Energy, 2008)

Integrated solar design. The "solar elements [are]... consciously incorporated in the architectural concept of the building envelope".(Hegger et al., 2008)

Latent thermal storage. Storage of energy or lack of energy in the change in phase of material as opposed to the change in temperature of the material.

Net zero energy costs. In a cost zero energy buliding, the amount of money the utility pays the building owner for the energy the building exports to the grid is at least equal to the amount the owner pays the utility for the energy services and energy used over the year.

Net zero energy emissions. A net-zero emissions building produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources.

Net zero site energy. A site zero energy buliding produces at least as much energy as it uses in a year, when accounted for at the site.

Net zero source energy. A source zero energy buliding produces at least as much energy as it uses in a year, when accounted for at the source. Source energy refers to the primary energy used to generate and deliver the energy to the site.

Net-zero energy building (ZEB). A building that feeds as much energy to the utility grid as the building takes from the grid over the course of a year.

Off-grid photovoltaic system. A solar system that produces electricity through the photovoltaic effect that is not connected to the electric grid.

Open loop. A conduit for moving heat that can receive fluid from a source outside the system or deliver fluid to a sink outside the system.

Passive solar system. A solar thermal system that relies on the buoyancy forces caused by temperature gradients within the system to circulate the heat transfer fluid.

Photovoltaic (PV) collector. A solar collector that generates electricity using the photovoltaic effect.

Pressurized glycol system. A solar thermal system that relies on the addition of an anti-freeze, often non-toxic glycol, to the heat transfer fluid to prevent fluid in the collectors and piping from freezing.

Renewable energy system. A system that generates energy from a source of energy will not be depleted during a time period of hundreds of human generations.

Residential building energy use. Energy that is used in buildings that serve as private households not including institutional living quarters. (U.S. Department of Energy, 2008)

Sensible thermal storage. Storage of energy or lack of energy in the change in temperature of a material as opposed to the change in phase of the material.

Solar fraction (SF). The portion of a demand for energy that is supplied by solar generated energy. This is the quantity of energy delivered from the solar thermal storage to the demand for energy divided by the total demand for energy. This does not account for any energy necessary to run the pumps or other energy consuming equipment of the solar system. The solar fraction can be evaluated for varying lengths of time including days, months, and years.

Solar gains. Solar radiation absorbed by the building structure or objects within the thermal envelope of the building through glass portions of the building envelope.

Solar thermal system (STS). A system for collecting solar radiation in the form of thermal energy to be supplied to an energy demand. These systems typically consist of an array of solar thermal collectors, a heat storage system, and a heat transfer fluid transport system.

Solar water heating (SHW). The process of heating water with solar radiation.

Specific Heat Capacity (C_p). The quantity of heat a material can hold per unit of mass and degree temperature change. The standard unit in the SI system is

J/kgK.

Storage heat loss coefficient $(UA)_s$. The product of the heat loss coefficient and the surface area of the storage vessel.

Storage volume. The volume of material that is used to store thermal energy in the solar thermal system.

Thermal Capacity. The quantity of thermal energy, measured in joules, that can a given mass can hold over a predefined temperature range.

Transient energy simulation tool (TRNSYS). A computer simulation tool developed to analyze solar thermal systems.

Transportation energy use. Energy consumed by "all vehicles whose primary purpose is transporting people and/or goods from one physical location to another". (U.S. Department of Energy, 2008)

Utilizability (ϕ). A radiation statistic defined as the ratio of the radiation that is above a critical level to the total radiation.

NOMENCLATURE

Utilizability

ϕ	utilizability (dimensionless) or latitude, (°)
$\bar{\phi}$, f-chart	utilizability f-Chart method

Collector Orientation Angles

β	collector slope, (°)
γ	surface azimuth angle, (°)
ϕ	latitude, (°); Also utilizability

Loads

T_{mains}	temperature of water delivered to building, ($°C$)
$T_{set,hw}$	set temperature of hot water, ($°C$)
m_{hw}	mass of the hot water demand for the month, (kg)
$C_{p,water}$	the specific heat of water, (j/kg K)
ΔT_{hw}	difference between hot water setpoint and water delivered to heater, (K)

Mains Temperature Correlation

$T_{out,avg}$	average annual outdoor temperature, (°F)
$T_{amb,avg}$	the annual average outdoor air temperature, (°F)
T_{mains}	the water mains temperature, (°F)
$T_{out,maxdiff}$	the maximum difference between monthly average ambient temperatures, (°F)

Collector Model

$\dot{Q}_u$	collector useful heat gain, (watts)
A_c	collection surface area, (m^2)

F_R	ratio of collector heat transfer/maximum possible collector heat transfer
S	absorbed solar radiation, (joules/m^2)
U_L	overall collector heat loss coefficient, (W/m^2 °C)
T_i	inlet temperature to collector, (°C)
T_o	outlet temperature from collector, (°C)
T_a	collector ambient temperature, (°C)
η	collector thermal efficiency
G_T	irradiance on a tilted surface, (joules/m^2)
$(\tau\alpha)_{av}$	average transmittance absorptance product
$\dot{m}$	heat transfer fluid mass flow rate, (kg/sec)
C_p	specific heat
$K_{\tau\alpha}$	incidence angle modifier
b_o	incidence angle modifier coefficient
$K_{\tau\alpha,t}$	transverse incidence angle modifier
$K_{\tau\alpha,l}$	longitudinal incidence angle modifier

Storage Thermal Losses

$(UA)_s$	storage surface area heat loss coefficient product, (W/K)
Q_s	thermal storage capacity, (joules)
T_s	storage temperature, (°C)
T'_a	storage ambient temperature, (°C)
ΔT_s	difference between temperature to load and temperature from load, (°C)
U	overall heat transfer coefficient, (W/m^2 K)
k	thermal conductivity, (W/m K)

ABSTRACT

Due to a growing awareness of the negative effects of the wide-spread use of fossil fuels as an energy source, there is a renewed interest in investigating ways to collect and utilize renewable forms of energy. Because buildings account for 39% of total energy use, they represent a significant opportunity for conservation of energy derived from non-renewable sources and implementation of renewable energy systems. Of the energy used by buildings in the United States the largest portion, 19.8%, is used for heating. Solar Thermal Systems (STS), which convert solar radiation into thermal energy, can meet a portion of this demand for heat.

The solar collection area and the capacity of the thermal storage determine the portion of a building demand for energy that can be met with solar energy produced by a STS. The fraction of the total energy requirement supplied by the STS, the solar fraction (SF), is typically limited by the availability of the solar resource and the seasonal mismatch between the supply of solar energy and the demands for thermal energy. There are a variety of analysis tools for determining the collector area and storage volume necessary to meet a desired solar fraction. This thesis uses the STS simulation capabilities of EnergyPlus extended by a Unix Bash shell script to determine a reasonable range of collector area and storage volume combinations for the space heating and water heating demands of a proposed net-zero energy elementary school building in New York City. Emphasis is placed on the potential for the STS to achieve high SFs through the use of very large storage volumes that are capable of storing energy collected in the summer season for use in the winter season. The achievement of high SFs, particularly for space heating demands, would be significant to the net-zero energy goal.

The results from the automated parametric study of the STS collector area and thermal storage capacity are presented as well as the sensitivity of the results to the type of collector and the weather file. The architectural implications of the simulation results are discussed. The scale of thermal storage necessary for seasonal energy storage using water within an insulated tank as the storage medium

is determined to be architecturally infeasible due to the volume required. A novel design for the storage of seasonal quantities of thermal energy within a building foundation and the regulation of the release of heat directly from the thermal store to the building is proposed as future work.

1. Introduction: Designing a Solar Thermal System for a Net-Zero Energy School

This thesis was written as a requirement of the Master of Science in Architectural Sciences Built Ecologies Concentration at the Center for Architecture Science and Ecology (CASE). CASE is a joint program between Rensselaer Polytechnic Institute (RPI) and Skidmore Owings and Merrill (SOM). The center provides a unique opportunity for collaboration between academia and professional practice as well as between students and professionals from different disciplines. The collaboration provides opportunities to test newly developed building systems within real projects. Additionally, SOM projects can provide invaluable case studies and test beds for developing next generation buildings systems.

This thesis studies the parameters involved in designing building integrated solar systems that are capable of offsetting a large portion of a building energy demand with solar generated energy, specifically within the context of a net-zero energy (ZEB) school in the Staten Island Borough of New York City. The portion of the energy demand met with solar generated energy is known as the solar fraction (SF) and is a key parameter when designing a solar thermal system (STS). Typically, solar fractions are limited to 50-80%[1] by the availability of the solar resource, the seasonal mismatch between the supply of solar energy, and the demands for thermal energy. When a STS is designed as a system of a building intended to generate as much energy as it consumes on an annual basis it is desirable to investigate strategies for achieving solar fractions higher than 80%.

[1]In Section 12.4 of Solar Engineering of Thermal Processes Duffie & Beckman (2006) provide a summary of work done by Buckles and Klein (1980) comparing the performance of forced circulation systems providing energy to meet typical residential hot water demands. A typical system from the study with one tank and three 1.44 m^2 collectors was able to provide 0.64 of an average daily hot water load of 300 liters from solar energy. Using the rules of thumb that typical consumption of hot water per person per day is 70 liters (18.5 gallons) and a collector area of 1.5 m^2 per person typical solar fractions range from 0.5 to 0.8 depending on the specific collector and the climate (Duffie & Beckman, 2006, p. 493). Additionally, Duffie & Beckman (2006) have drawn the conclusion from Braun (1980) that a system with a storage volume to collector ratio of 75 liters/m^2 and a collector area of 100 m^2 would provide 0.85 of a space heating load in Madison, Wisconsin (Duffie & Beckman, 2006).

For a given load or demand for energy the collection area and the thermal storage capacity are the design parameters with the greatest influence on the SF (Duffie & Beckman, 2006, p.659). EnergyPlus is a building energy simulation tool with the capability to model the performance of STS's when these design parameters are varied. It was applied in this thesis with the addition of custom Unix Bash shell scripts to perform parametric simulations of STS's. EnergyPlus was selected because it is available, verified, and undergoing active development. An extensive comparison of the possible simulation tools is presented in Appendix A.

Thermal storage with the capacity to retain heat from the summer into the winter (seasonal storage) is proposed as the most practical way of achieving high SF's given the latitude and climate of NYC. The ideal collector tilt, orientation, and storage capacity (storage volume) for the production of energy with a STS often conflict with other parameters important to the overall architectural design. These architectural parameters include aesthetics, space available for mechanical systems, and human factors that are difficult to quantify. This thesis concludes with a suggestion for reconciling the design parameters of a STS necessary to achieve high solar fractions with the architectural design requirements.

This thesis is organized in the following chapters: Theoretical Background: Importance of High Solar Fraction Renewable Energy Systems to Net-Zero Energy Buildings, Technical Background: Design and Simulation of Solar Thermal Systems, Case Study: Applying Parametric EnergyPlus Simulations to the Design of a Solar Thermal System for a Net-Zero Energy School in NYC, Results: Collector Area and Storage Volume Combinations Appropriate to the Net-Zero Energy School, Future Work: Low Temperature Seasonal Storage with Passive Energy Delivery, and Conclusions. The Theoretical Background Chapter explains the importance of buildings as large consumers of energy and provides a brief summary of the arguments for reducing the use of fossil-fuel based energy. A discussion of the term zero energy building is presented as it is relevant to the case study and is part of the justification for the research into strategies for designing a STS with a high SF. Additionally, the most common methods for on-site generation of renewable energy are discussed with a focus on STS's. The conceptual categories additive, integrated, and adaptive describing the relation of the STS to the building design are introduced.

The Technical Background Chapter describes the basic components of a solar thermal system and typical system designs. The most commonly used design methods and software tools are presented and EnergyPlus with the addition of a custom Bash shell script is selected as an appropriate tool for the parametric study of a STS for the case of the ZEB School. The parameters, inputs, and the Bash shell script necessary to perform the parametric EnergyPlus simulations are described. The parameters described include buildings loads, collector parameters, and thermal storage tank heat loss coefficients.

The Case Study Chapter describes the application of EnergyPlus and the Bash shell script to the specific case of a ZEB school in the borough of Staten Island, NYC. This involves obtaining predictions of building loads, both space heating and domestic water heating, for a proposed school design. Different collector types are evaluated based on performance parameters and architectural aesthetics and a collector is selected for use in the parametric EnergyPlus simulations. Approximate rates of heat loss from various thermal storage configurations are calculated and presented. A weather data file for a location as close as possible to that of ZEB school site on Staten Island is selected for use in the simulations.

The Results chapter presents written and graphic results from the design of a high SF STS for a ZEB school. The range of collector area and thermal storage combinations that provide reasonable SF's for the case study building are presented. Additionally, the monthly solar fractions for two of the selected systems are presented. For one of the selected systems the results of sensitivity analyses of the collector type and weather file are presented.

The Recommendation for Future Work chapter describes a potential method for achieving high solar fractions through the use of seasonal scale thermal storage that would not require a large storage tank. The proposed system would provide seasonal storage capacities through low temperature storage within a building foundation. The potential for controlling the delivery of energy directly to the building through temporally varying floor slab thermal properties is the crux of the proposed future work. A thermal storage system with this capability could increase the adoption of seasonal scale thermal storage and thus increase the prevalence of STS's that provide SF's in the range of 80-90%. The ability to provide SF's of this magnitude is particularly important within the context of the ZEB school, which must generate as much energy as it consumes annually.

2. Theoretical Background: Importance of High Solar Fraction Renewable Energy Systems to Net-Zero Energy Buildings

This chapter situates the thesis relative to the issues of high building energy demand, the environmental effects of energy generated from fossil fuels, the concept of the net zero-energy building (ZEB), and architectural integration of renewable energy systems. The first section situates building energy use within the context of total energy use in the United States and breaks down total demand for energy of buildings into energy demands that can be meet with thermal energy produced by STS's. The second section, The Case for Reducing The Use of Fossil Fuel Derived Energy by Buildings, briefly describes the links between building demands for energy, the production of CO_2, and the global energy balance. The third section, Zero Energy Buildings: Definitions, Reducing Energy Use, Generating Renewable Energy On-site, describes the concept of the net zero-energy building (ZEB) and the influence of the ZEB concept on the design of building connected renewable energy systems, particularly STS's. The third section includes strategies for improving the efficiency of buildings and forms of renewable energy generation most commonly applied to buildings. Finally, in the last section, Integration of Architecture and Renewable Energy Systems, the conceptual categories additive, integrated, and adaptive describing the relation of the STS to the building design are introduced with examples of built projects.

2.1 Identifying Building Energy Use Relevant to Solar Thermal Systems

The U.S. Department of Energy Databook provides statistics and visualizations of the energy consumption of buildings in the United States. The Energy Efficiency and Renewable Energy department of the U.S. DOE has organized energy use in four broad categories: residential buildings, commercial buildings, transporta-

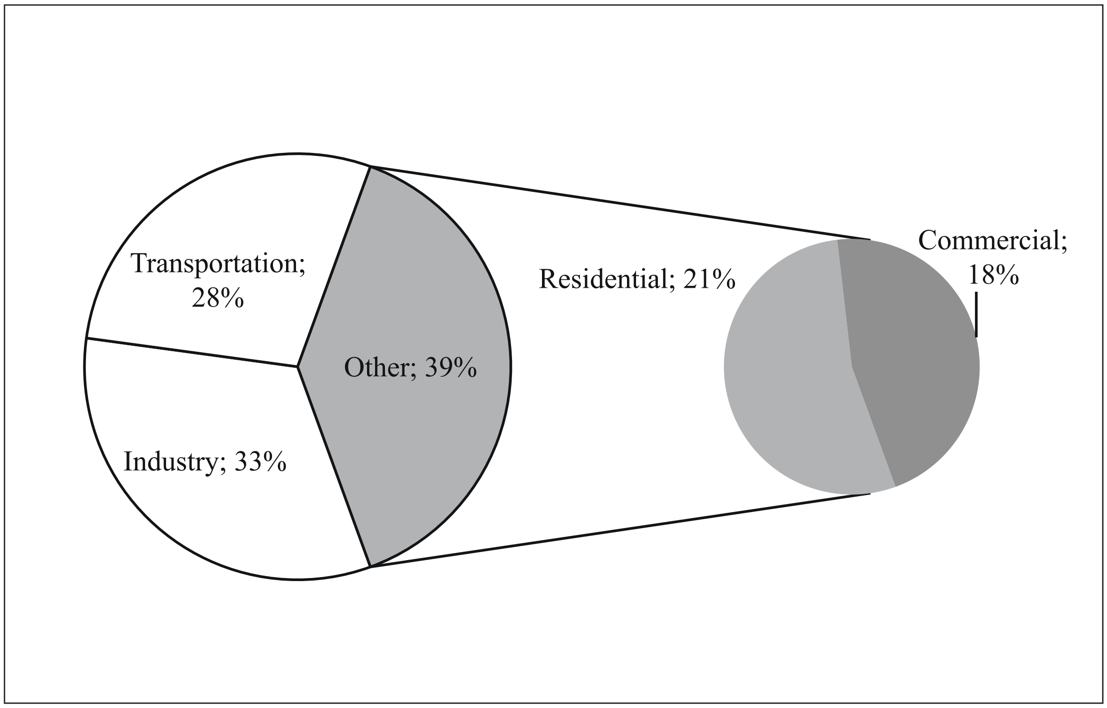

Figure 2.1: Building share of US primary energy consumption for 2006 (U.S. Department of Energy, 2009).

tion, and industry. Residential building energy use is defined as energy that is used in buildings that serve as private households and does not include "institutional living quarters". Commercial building energy use is defined as energy that is used by buildings occupied by businesses, government organizations, and institutional living quarters. Transportation energy is defined as the energy consumed by "all vehicles whose primary purpose is transporting people and/or goods from one physical location to another". Industry energy use includes energy "of all facilities and equipment used for producing, processing, or assembling goods" (U.S. Department of Energy, 2008). The pie chart in Figure 2.1 shows the division of U.S. energy consumption between these sectors for 2006. In 2006, buildings were responsible for 38.9% of energy use in the U.S. This is a substantial fraction of the total energy use in the U.S. which makes research in reducing the use of fossil fuel based energy by buildings important to decreasing the total demand for fossil fuel based energy in the U.S. The energy consumption of buildings can be further examined by the end use of the energy within the building. These uses include but are not limited

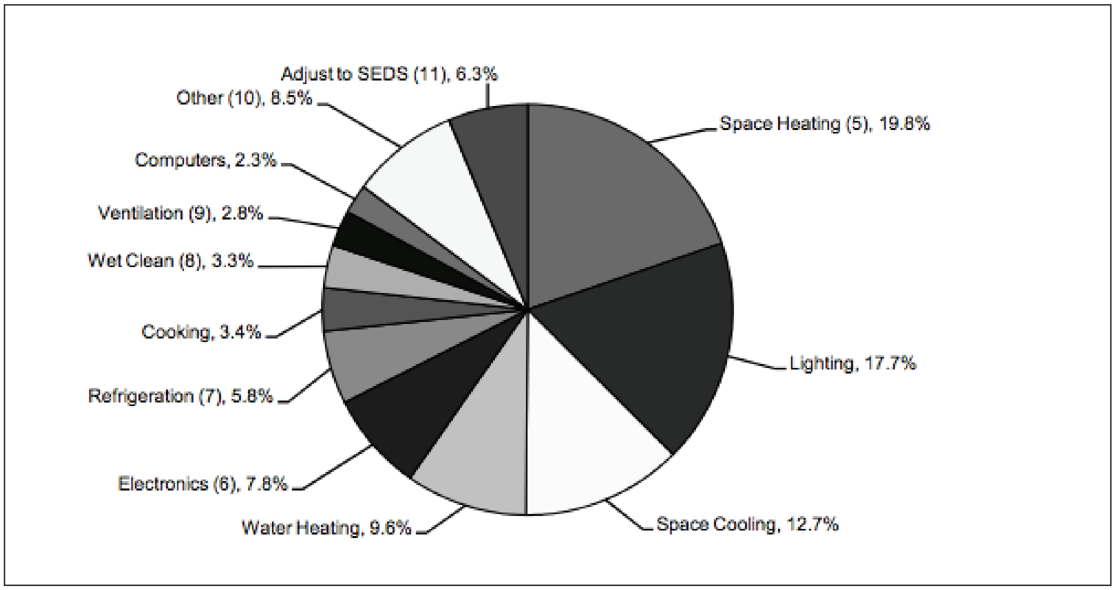

Figure 2.2: 2006 U.S. building energy end-use splits (U.S. Department of Energy, 2009).

to water heating, space cooling, space heating, and appliance operation. Figure 2.2 shows in percentages how much energy within the building the final uses require. Of these end-uses, STS can directly provide energy to meet space heating and water heating energy demands. The energy demands for space heating and water heating are cumulatively responsible for 29.4% of building energy demand. Considering the overall energy use of buildings in the U.S. from Figure 2.1, 38.9%, and the demand for space heating and water heating within buildings, 29.4%, these categories account for roughly 11% of the total energy demand of buildings in the U.S. If STS with high solar fractions can be implemented on a broad scale a significant amount of this energy could be provided by solar radiation with a great reduction in the demand for fossil fuel based energy.

2.2 The Case for Reducing The Use of Fossil Fuel Derived Energy by Buildings

In 2007, energy demands for electricity and heating accounted for 40% of the total 26.6 Gt of CO_2 emitted (Quadrelli & Peterson, 2007). Carbon dioxide as well as water vapor, methane, nitrous oxide, and chlorofluocarbons are all known as green-

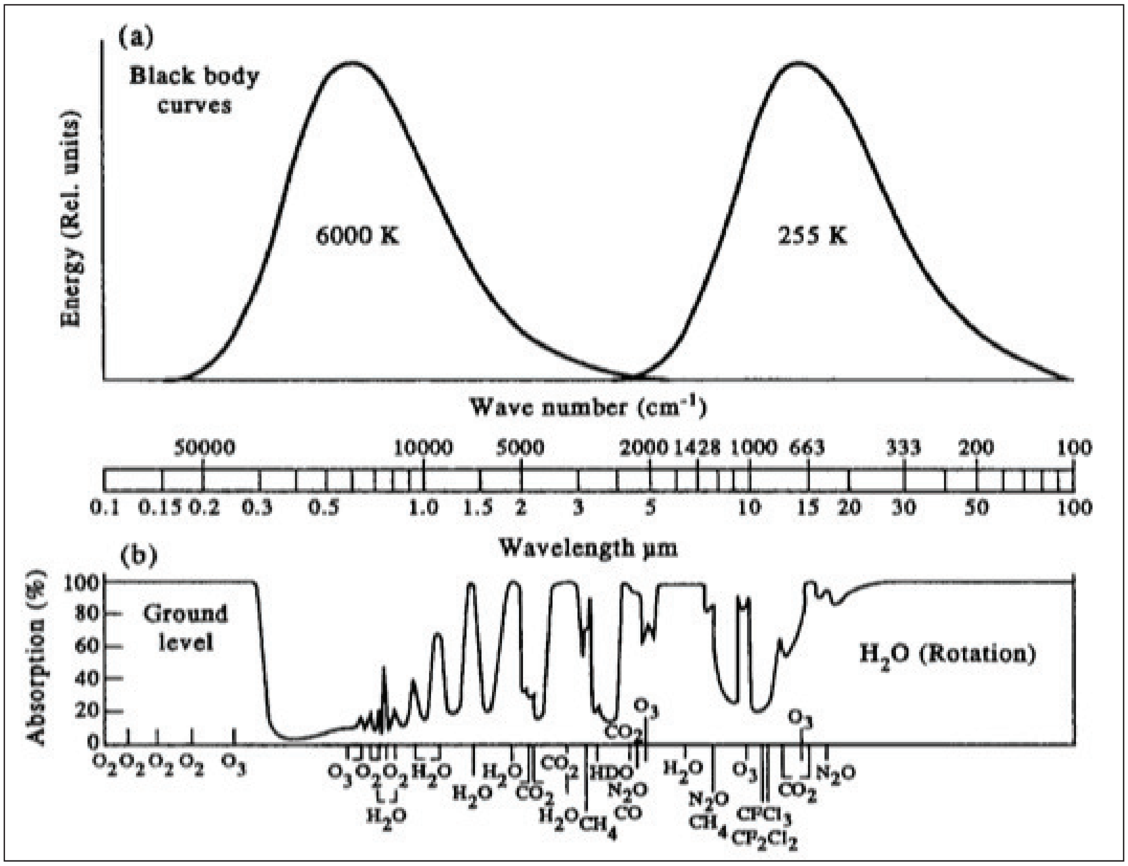

Figure 2.3: Spectral solar and terrestrial radiation and greenhouse gas absorption (Jain, 1993).

house gases due to their ability to absorb long-wave radiation (Jain, 1993). The term greenhouse is used because the increase temperature of the earth due to greenhouse gas absorption of long-wave radiation is similar to the increase in temperature of the interior of a greenhouse due to the absorption of long-wave radiation by the glass of the greenhouse. The ability of carbon dioxide and water vapor to absorb solar radiation is a result of the physical structure of their molecules. Carbon dioxide and water vapor are both triatomic molecules and the bonds between their atoms can absorb long-wave radiation as vibrational or rotational energy, while diatomic molecules like oxygen are only capable of absorbing higher energy, shorter-wavelength, radiation (Jain, 1993). Carbon dioxide (CO_2) gas absorbs electromagnetic radiation strongly in the range of radiation that is emitted by the surface of the earth, long-wave radiation. However, CO_2 does not absorb shorter wavelength electro-magnetic radiation.

The massive increase in the amount of CO_2 gas in the atmosphere due to human combustion of fossil fuels for energy is leading to an increase in the global mean temperature, due to the increased trapping of long-wave radiation. Although the greenhouse effect of a single CO_2 molecule is much less than a single molecule of the other greenhouse gases, the production of CO_2 is two to four times higher than that of the other gases and therefore contributes the most to enhancing the greenhouse effect (Jain, 1993). STS's capture energy from incident solar radiation and therefore do not add to the amount of CO_2 present in the atmosphere.

2.3 Zero Energy Buildings: Definitions, Reducing Energy Use, Generating Renewable Energy On-site

The concept of the net zero-energy building was defined by Torcellini, Pless, Deru, & Crawley in the US Department of Energy report "Zero Energy in Buildings: A Critical Look at the Definition" as "a residential or commercial building with greatly reduced energy needs through efficiency gains such that the balance of energy needs can be supplied with renewable technologies" (2006). A crucial point to the concept of the ZEB is the use of the idea of 'net' zero energy, which will be discussed further in the following paragraph. The definition quoted above is general in that it does not specify where the renewable energy may be physically generated to count towards the energy balance of the ZEB. This point was recognized as important by the authors of the report, who offered four specific definitions for ZEBs that account for the location of the renewable energy generation. The distinction that this definition makes between the reduction of energy needs through efficiency measures and the supply of the balance of energy needs through renewable energy is vitally important to the process of designing a ZEB. A design approach that focuses on implementing the two parts of the definition sequentially, efficiency followed by renewable energy production, may miss opportunities to maximize the production of renewable energy that could lead to a more successful realization of the ZEB goal. The selection of the type of renewable energy best suited to meet the balance of energy needs is determined by the building program, the building location, and the economics of the project. The forms of renewable energy most commonly used to meet building energy demands are photovoltaic electricity generation, solar generated thermal energy, and wind generated electricity.

The definition of the net zero-energy building presented above assumes that the building and the renewable energy systems providing energy to the building are connected to the electric grid. Grid interconnection allows the building to draw energy from the grid when the renewable energy systems are not able to meet the building demand for energy. Conversely, the renewable energy systems can deliver energy to the grid if the building need for energy is not as great as the production of energy by the renewable energy systems. This exchange between the grid and the renewable energy system assumes that the grid is capable of both supplying and absorbing energy whenever necessary based on the interaction of the unique temporal fluctuations of the the renewable resource and the building energy demand. The mismatch between the supply of renewable energy sources and demands for energy is a fundamental issue facing the implementation of renewable energies in general; it can be partially overcome with energy storage. Unfortunately, the energy storage technologies available today are often incapable of meeting the challenge of bridging the gap between intermittent renewable energy sources and demands for energy. The concept of the net-zero site energy building essentially utilizes the energy grid as a form of energy storage. This approach is effective if the grid has the capacity to receive excess energy from the grid when necessary and to deliver energy to the building when necessary. In most areas within the United States this is currently an effective strategy because the generating capacity of grid-connected renewable energy systems is small compared to the capacity of the non-renewable, and dispatchable electricity producing systems feeding the grid. However, as the number of grid-connected renewable energy systems increases and the size of the renewable energy systems increases this approach may need to be reconsidered or improvements to the capacity of the electric grid to cope with variable sources of power will need to be improved (Torcellini et al., 2006).

Torcellini et al. provide four definitions of a ZEB that are useful in defining the goals of ZEB project and can have a significant effect on the design of a ZEB building:

- **Net Zero Site Energy.** A site ZEB produces at least as much energy as it uses in a year, when accounted for at the site.
- **Net Zero Source Energy.** A source ZEB produces at least as much energy as it uses in a year, when accounted for at the source. Source energy refers to the primary energy used to generate and deliver the energy to the site. To calculate a buildings total source energy, imported and exported energy is multiplied by the appropriate site-to-source conversion multipliers.
- **Net Zero Energy Costs.** In a cost ZEB, the amount of money the utility pays the building owner for the energy the building exports to the grid is at least equal to the amount the owner pays the utility for the energy services and energy used over the year.
- **Net Zero Energy Emissions.** A net-zero emissions building produces at least as much emissions-free renewable energy as it uses from emissions-producing energy sources. (2006)

The site ZEB definition makes it easy to assess if the building is meeting the ZEB goal through metering at the site. The energy delivered to the site and the energy delivered to the grid can be easily determined through net metering. The site ZEB definition allows for renewable energy installations to be installed on site, but not within the actual footprint of the building. Torcellini et al. (2006) provide a hierarchy that ranks various options for the supply of renewable energy necessary to achieve a ZEB. Within this hierarchy they rank renewable energy that can be generated within the footprint of a building higher than energy that can be generated within the site boundaries. Renewable energy generated within the building footprint is preferable to energy generated within the site boundaries because the area outside the building footprint may be subject to future use that displaces the renewable energy production.

The net zero source energy definition provided by Torcellini et al. (2006) takes into account the inefficiencies of the energy generation and distribution. Torcellini et al. (2006) note that this definition promotes the use of natural gas on-site because there are more conversion processes and thus greater inefficiency with the production and delivery of electricity compared to the delivery of natural gas. However, determining appropriate conversion factors for calculating source energy from energy consumption measured on-site can be difficult and will depend on the conversion processes between the source and the site. An important characteristic of both the site and source ZEB is the omission of how these accounting methods deal with the cost to the owner or operator of the energy use of a building. A building that meets the requirements of the site or source ZEB definition may not achieve a similar reduction in utility bills (Torcellini et al., 2006). For example, a building that has a high summer electrical demand for building cooling may have expensive utility bills even if a renewable energy system is capable of offsetting the summer time electrical demands during cooler portions of the year.

The third definition of a ZEB is based on the net costs for energy for the year. Torcellini et al. (2006) describe the cost ZEB as the most difficult of the definitions to achieve for a commercial building and suggest that it may not be well-suited for wide-scale implementation. Utility rates fluctuate due to factors beyond the control of building owners and operators and must include the costs of maintaining energy distribution. Torcellini et al. (2006) expect, based on the experience of water distribution networks, that the cost of maintaining the distribution network would increase as the the number of ZEBs increases.

The final ZEB definition, the zero emissions building, like the source ZEB definition requires the use of conversion factors to estimate the emissions associated with the energy used by the building. The zero emissions building is much more dependent on the type of process or processes used to generate the electricity consumed by the building. A building located in a region with significant sources of emission free energy, like hydropower, can achieve the zero emission goal much more easily than a building in a region with a large amount of emission producing energy generation.

The first definition of a zero-energy building is attractive due to the ease of implementation provided by net-metering. However, if the goal of the project is to reduce the CO_2 emissions associated with the building energy use then the

Table 2.1: New York Total Electric Power by Energy Source, 2008 (U.S. Energy Information Administration, 2010)

Primary Energy Source	Net Generation (Thousand Mwh)	Share of State Total (Percent)
Nuclear	43,209	30.8
Coal	19,154	13.7
Hydro and Pumped Hydro	26,051	18.6
Natural Gas	43,856	31.3
Other	987	0.7
Other Renewable	3,319	2.4
Petroleum	3,745	2.7
Total	140,322	100.0

zero emission building may be a better goal. The zero-emission goal as defined by Torcellini et al. (2006) counts nuclear generated electricity as an emission free source. Because this thesis focuses on the design of a STS for a school in NYC, the makeup of energy is relevant to consider. The electric power generated in NYC in 2008 by type of electricity generation is presented in table 2.1.

Considering that the portion of energy generated from emission free sources is approximately half of the total energy production for NY state the zero emissions building could be significantly easier to achieve than the zero-site energy building if the energy supplied to Staten Island has a similar generation makeup as the state as a whole. However, there may be other factors that make the emission free sources of electrical energy less desirable if the goal of the building project is to minimize the total environmental impact of the operation of the building. Considering the limited scope of this thesis and the well-defined boundaries provided by the site ZEB definition, the site ZEB definition will be adopted as a design parameter.

2.3.1 Approaching Net-Zero Energy Buildings by Reducing Energy Demand

Because renewable energy systems that can generate enough energy to meet an entire building energy need are prohibitively expensive, design of a ZEB requires measures to reduce the energy demand of the building compared to a typical building. A number of common strategies are employed to reduce building energy

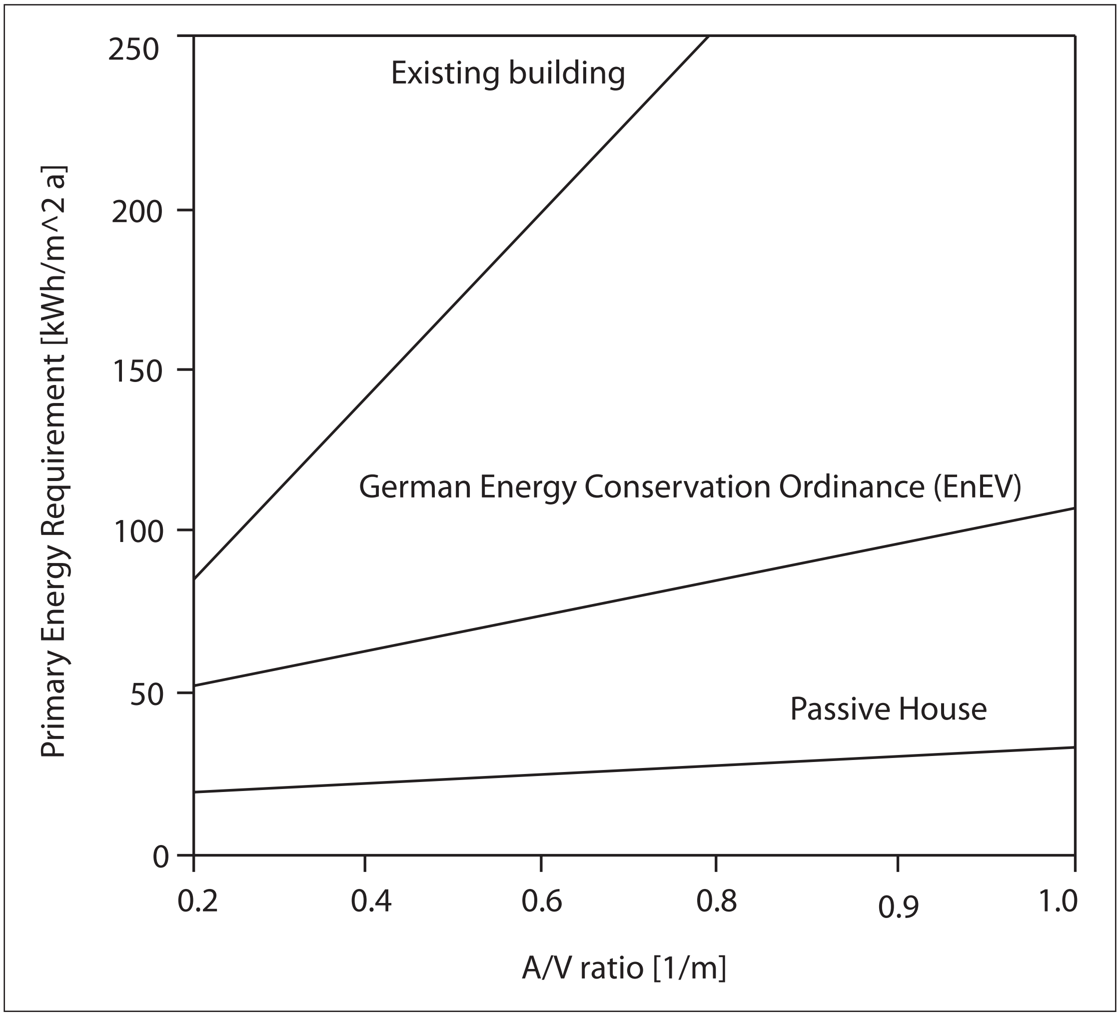

Figure 2.4: Compactness of a building versus annual energy demand (Hegger et al., 2008).

demands. These strategies vary depending on the particular site and climate. The most common strategies involve optimizing the building area to volume ratio, controlling solar gains, and minimizing transfer of energy through the building envelope (Hegger et al., 2008).

The building area to volume ratio (A/V ratio), when used to describe the thermally insulated volume of a building, can be referred to as the compactness of the building (Hegger et al., 2008). Buildings that have insulated volumes that more closely resemble a cube have a lower ratio of surface area to volume and therefore lose less heat to the environment. This concept is illustrated in Figure 2.4 which shows the annual energy demands of three building types for varying degrees of compactness. Figure 2.4 also illustrates the effect of high thermal insulation and low air infiltration on the energy needs of the building. The line denoting the energy use for a building designed to the Passive House standard, which requires a tight building envelope, shows much less change with change in compactness compared to an 'existing building'. When designing a ZEB compactness is useful for reducing the building demand for energy, but it may also reduce the surface area available for collecting and transforming solar radiation into usable electric or thermal energy. This contradiction increases the importance of a well insulated envelope to the design of a ZEB.

Orienting a building in a way that maximizes or minimizes solar gains depending on the climate and the demands of the building program is important to reducing the building energy consumption. The term solar gains must be better defined in order to differentiate between energy that is absorbed by the building structure itself, that may or may not be usable, and energy that might be collected through the use of an active solar system, photovoltaic or thermal. In this thesis solar gains will refer to solar radiation absorbed by the building structure or objects within the thermal envelope of the building through glass portions of the building envelope. Designing buildings to utilize incident solar radiation for solar gains when there is a need for thermal energy to maintain comfort and to avoid solar gains when there is a need to remove heat from the building to maintain comfort, requires an understanding of the effects of latitude, slope, and azimuth on the quantity of solar energy received by a surface. The slope is defined as the "angle between the plane of the surface in question and the horizontal" and the azimuth is defined as the "deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, with zero due south, east negative, and west positive" (Duffie & Beckman, 2006). Duffie & Beckman (2006) performed an analysis of the effect of slope and azimuth on the quantity of radiation received by a surface. Figure 2.5 shows the annual trends resulting from this analysis. The analysis was done for a surface at a latitude of 45°. The slopes of the surfaces analyzed range from zero to ninety degrees. It is clear from Figure 2.5 that the radiation on the surface is higher during the summer for surfaces with lower slope and higher during the win-

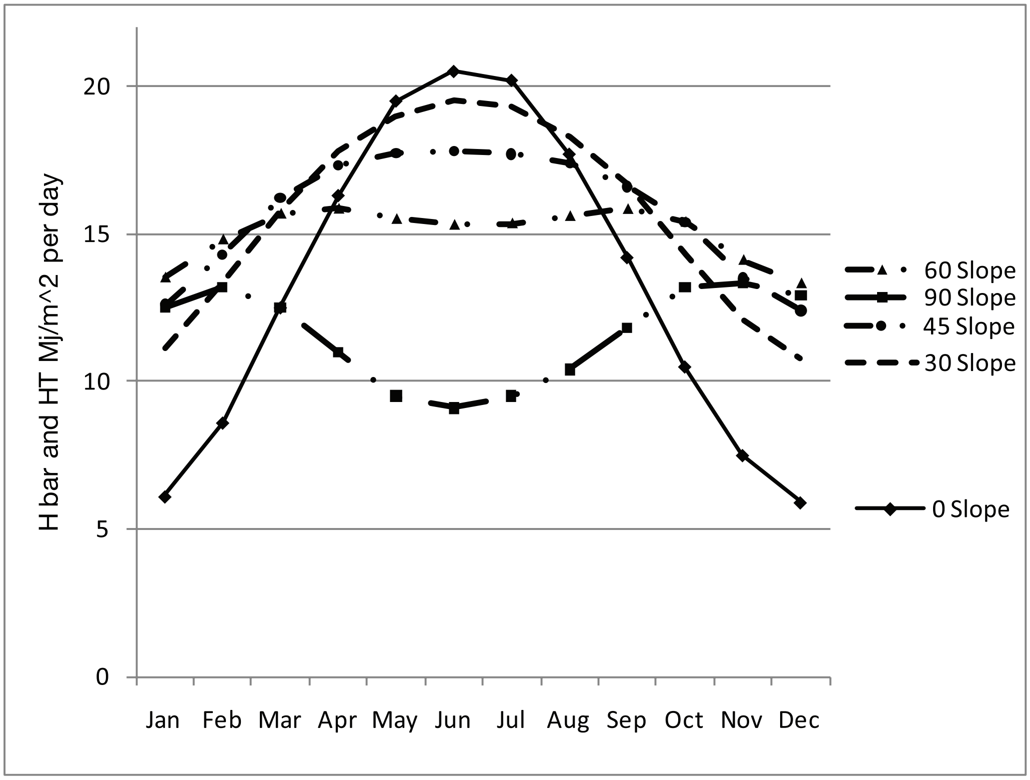

Figure 2.5: "Variation in estimated average daily radiation on surfaces of various slopes as a function of time of year for a latitude of 45°, $\bar{K}_T$ of 0.50, surface angle of 0°, and a ground reflectance of 0.20" (Duffie & Beckman, 2006).

ter for surfaces with higher slopes. The extreme angles show much more variability throughout the year when compared to the angles closer to the latitude. These trends suggest that for buildings in higher latitudes, that typically need more energy for heating than cooling on an annual basis, surfaces of the building or surfaces of active solar collection should be at steeper angles to collect energy when it is most needed.

Figure 2.6 shows the relationship between the cumulative annual energy incident on a surface, the slope of the surface, and the azimuth of the surface. The top line in the graph showing the total annual energy versus the slope is the total annual energy, while the lower line is the total energy for the winter months, December through March. The top line shows a maximum around 40 degrees, which is approximately the same as the latitude. Thus, the rule of thumb to tilt solar collecting surfaces equal to latitude for maximum annual energy production. It is

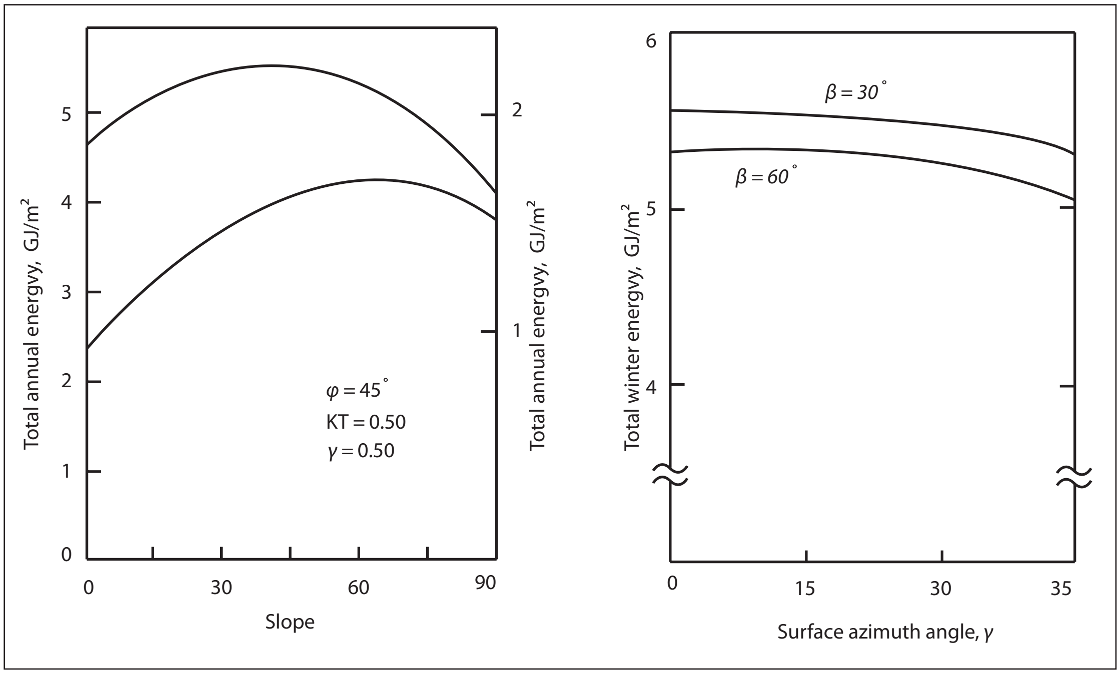

Figure 2.6: "Variation of total annual energy and total winter (December to March) energy as a function of surface slope for a latitude of 45°, $\bar{K}_T$ of 0.50, surface angle of 0°, and a ground reflectance of 0.20" (Duffie & Beckman, 2006).

important to note that the total annual energy calculated in this analysis is the total quantity of energy that is incident on the surface for the year. Due to the potential for mismatch between the availability of solar radiation and the demand for energy this rule of thumb does not guarantee the greatest reduction in the use of non-renewable energy. Duffie & Beckman (2006) observe that the "changes in total annual energy are less than 5% for slopes of 20° more or less than the optimum". The peak total annual energy for a set slope with a varying azimuth angle is for an azimuth angle of 0°, or a surface pointed due south. This peak output is reduced minimally for azimuth angles that are within 30-40° east or west of due south.

The conclusions drawn from Figures 2.5 and 2.6 are important to the design of a ZEB because of the effect on both the energy efficiency of the building and the effectiveness of renewable energy systems installed on building surfaces. The ideal slope for the collection surfaces of a renewable energy system is near latitude, which is in opposition to the typical orthogonal design of buildings, especially in middle latitudes. Architectural designs that are able to achieve energy efficient buildings, while providing large surface areas near latitude will achieve ZEB goals more easily than buildings that do not consider both of these design challenges in early design phases.

2.3.2 Approaching Net-Zero Energy Buildings by Generating Renewable Energy On-Site

The most common forms of renewable energy generation that are added to or integrated with buildings are wind energy systems, photovoltaic systems, and solar thermal systems.

Solar photovoltaic (PV) systems are the most common renewable energy systems used in ZEBs. Out of six high performance buildings analyzed by Torcellini et al. (2004) four of them utilized some type of photovoltaic system, while only one of the buildings utilizes any other form of active renewable energy generation. PV systems require relatively little maintenance and are not technically difficult to install. PV systems integrated with or added to buildings can be either off-grid or grid-tied systems. Off-grid systems are most common in remote locations and often incorporate a battery system to store energy produced by the PV system when the demand does not consume all the energy generated. Grid tied systems offer a number of advantages when compared to off-grid systems including lower installation costs, lower maintenance, and less complexity to maintain a stable energy supply. For these reasons grid tied systems are more common than off-grid systems and are better suited to supplying energy to ZEBs.

Hegger et al. (2008) describe electric energy as the 'highest form' of energy because it can be converted into other forms of energy, such as thermal or mechanical with relative ease. Additionally, for ZEB projects that are intended to meet the net zero source energy definition the combination of the conversion factors for calculating the source energy and substitution of energy derived from natural gas or heating oil for electric energy generated on-site can make a renewable energy system that generates electricity more desirable than one that generates thermal energy. Due to the relative ease of concealing electrical wiring compared to insulated piping and the slimmer profile of flat plate photovoltaic modules compared to flat plate solar thermal collectors, architectural integration of PV systems is less difficult than architectural integration of solar thermal systems. Finally, PV systems are better known to the public, which encompasses the owners or developers who might fund a ZEB project.

Solar thermal systems are the second most common type of renewable energy system integrated with or added to buildings after PV systems. Solar water heating (SHW) is the most common use for solar thermal systems that supply energy to buildings. SHW systems began modern commercial development during the 1960s (Kalogirou, 2004), but were being developed commercially as early as the 1890s (Shukla, Buddhi, & Sawhney, 2009). STS designed to provide energy to meet building space heating demands are similar to SHW systems and have been installed and researched extensively since the 1970s (Duffie & Beckman, 2006). STS's importance to the ZEB concept would be greatly increased by the ability to store large quantities of thermal energy on-site in an economically and architecturally acceptable system. Depending on the demands of a particular building electrical energy may not be the highest form of energy. With the ability to store large quantities of energy on-site the value of thermal energy in heating climates is equal to or greater than the value of electrical energy within the context of the ZEB. The basic components and common system designs of STS are discussed in more detail in Section 3.1.

2.4 Integration of Architecture and Renewable Energy Systems

Traditionally, the renewable energy systems described in Section 2.3.2 have been retrofitted additions to buildings rather than integrated within the architectural design of the building. Hegger et al. (2008) in the Birkhauser reference *Energy Manual: Sustainable Architecture* propose three categories for classifying the way solar technology interfaces with architectural design: addition, integration, and adaption. Buildings in the addition category are designed without regard to solar technology, while buildings in the integration category have "solar elements ... consciously incorporated in the architectural concept of the building envelope" (Hegger et al., 2008). Adaptive buildings have forms that maximize the use of the solar resource, like facades angled to increase the incident radiation. The International Energy Agency in their report on Renewables for Heating and Cooling determined that "Architectural design plays a major role for a broader market penetration of solar heating and cooling options. The components need to become standardised elements of modern buildings rather than retrofitted" (International Energy Agency, 2007, p. 41). To meet this goal the mechanical systems that utilize renewable sources of energy for heating and cooling must not only become "standardised elements of modern buildings" but must also become multi-functioning elements of buildings that fulfill structural, architectural, and mechanical functions.

The remainder of this section presents three examples of STS that are relevant to this thesis due to their achievement of high solar fractions or integration of STS components with the building. Two of the systems are notable for achieving high solar fractions through the use of seasonal scale thermal storage: Drake's Landing and an apartment building in Berne, Switzerland. In the final example Soifer & Stickney (2010) describes how the concrete foundation of a residential building can store energy from an active STS.

Drake's Landing is a group of energy efficient houses that are heated through a district heating loop, which is supplied with energy from a borehole thermal energy storage (BTES) field and a 2,293 m^2 array of solar thermal collectors (Sibbitt et al., 2007). The system is unique in North America due to its use of the BTES to store energy seasonally. Figure 2.7 shows a simple schematic of the Drake's Landing STS and a photograph showing the houses and the garage mounted solar thermal array. This STS although designed prior to the construction of the houses that it supplies energy to is not well integrated into the architecture of the homes. Utilizing the solar collectors as the roof of the garages rather than mounting the collectors on a traditional roof could have potentially reduced the investment cost associated with the collectors. The thermal storage systems at Drake's Landing are not integrated within the building. The thermal storage consists of two short term thermal storage tanks in addition to the BTES. These tanks are housed in their own small building adjacent to the houses (Sibbitt et al., 2007). The Drake's Landing STS was able to provide a solar fraction of 55% over a year spanning 2007-2008 and 60.4% over

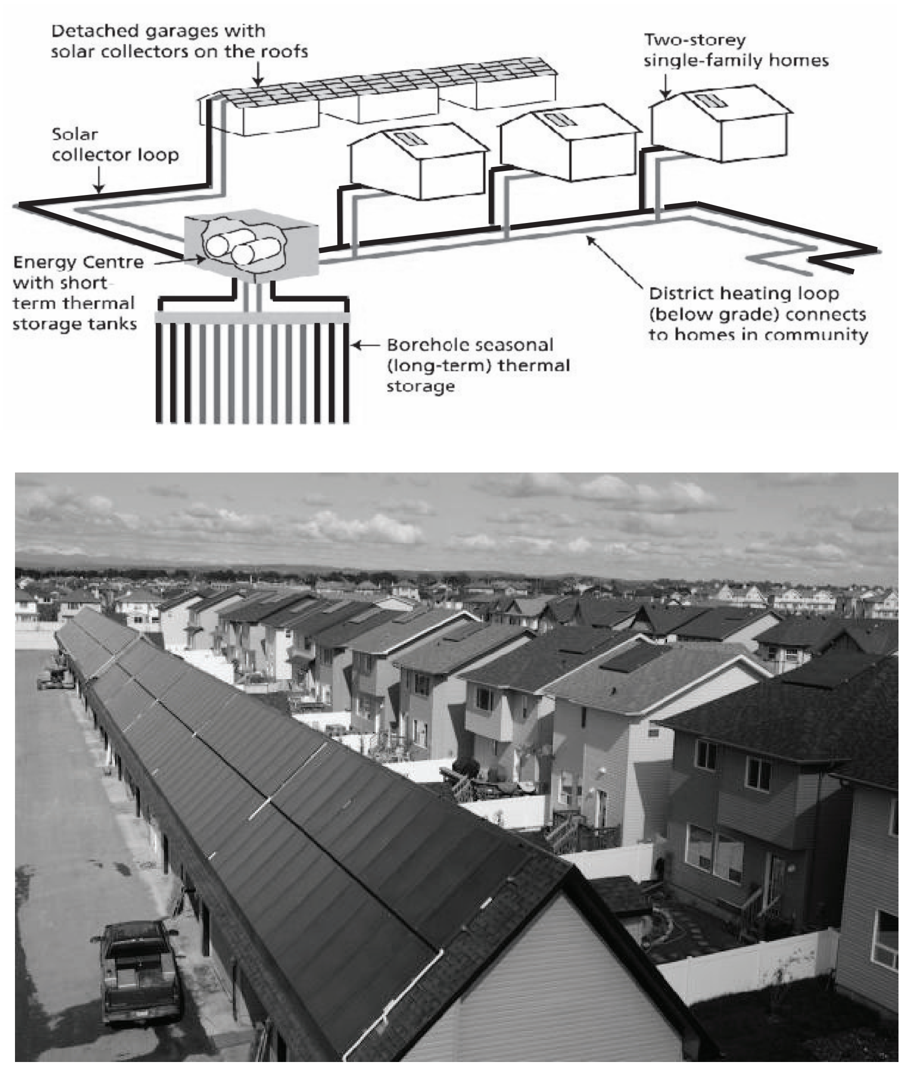

Figure 2.7: Schematic (Sibbitt et al., 2007) and photograph (Young, 2010) of Drake's Landing in Alberta Canada.

a year spanning 2008-2009 (Science Applications International Corporation, 2010). The BTES system requires several yearly cycles to reach its operational temperature. Based on early assessment of the system in 2007, it was expected to take five years to reach the design SF of 90% (Sibbitt et al., 2007). As of summer 2011, the Drake Landing STS was operating with an annual SF of 86% as reported by the publicly available online monitoring system (Drake Landing, 2011). The Drake's Landing

STS system is an important achievement relevant to the design of ZEBs. STS that are capable of providing high SF's, near 90%, are vitally important to net ZEB since the renewable energy systems must ultimately provide all the energy requirements of the ZEB over the course of a year. Additionally, STS that utilize thermal storage with high capacities to achieve high SF reduce the dependency on the grid for 'storage'. This capability will become increasingly important as renewable energy systems become more prevalent.

The apartment building in Berne, Switzerland features a STS that was designed by Jenni Energietechnik AG to provide 100% of the water and space heating needs of the building (Jenni Energietechnik, 2011b). Jenni Energietechnik (2011b) claim that this is the first apartment building in Europe to achieve a 100% SF for space heating energy demands. A schematic of the STS and a photograph of the apartment building are shown in Figure 2.8. This building is an example where the STS has been fully integrated within the design of the buildings. The solar collectors are designed so that they can function as the upper weather resistant layer of the south facing roof of the building (Simons & Firth, 2011). The large solar storage tank is of similar scale as the apartment building itself and was installed prior to the construction of the building (Jenni Energietechnik, 2011b). The STS in this building is much more integrated than the Drake's Landing STS. Although there is an important difference in the scale of these projects, the level of integration exhibited by the European project is something that should be sought after in projects in North America. Early cooperation between the designers of renewable energy systems and designers of buildings, as exhibited by this project, is vital to the success of ZEB projects. Additionally, early cooperation allows for better integration of renewable energy systems within the traditional building components, which can both improve the performance of the renewable energy system and the quality of the architecture.

Soifer & Stickney (2010) provide a practical discussion of the thermal capacity of concrete in comparison to water. This discussion describes how the concrete foundation of a residential building can replace a storage tank as the thermal storage for an active solar thermal system that provides energy to meet space and water

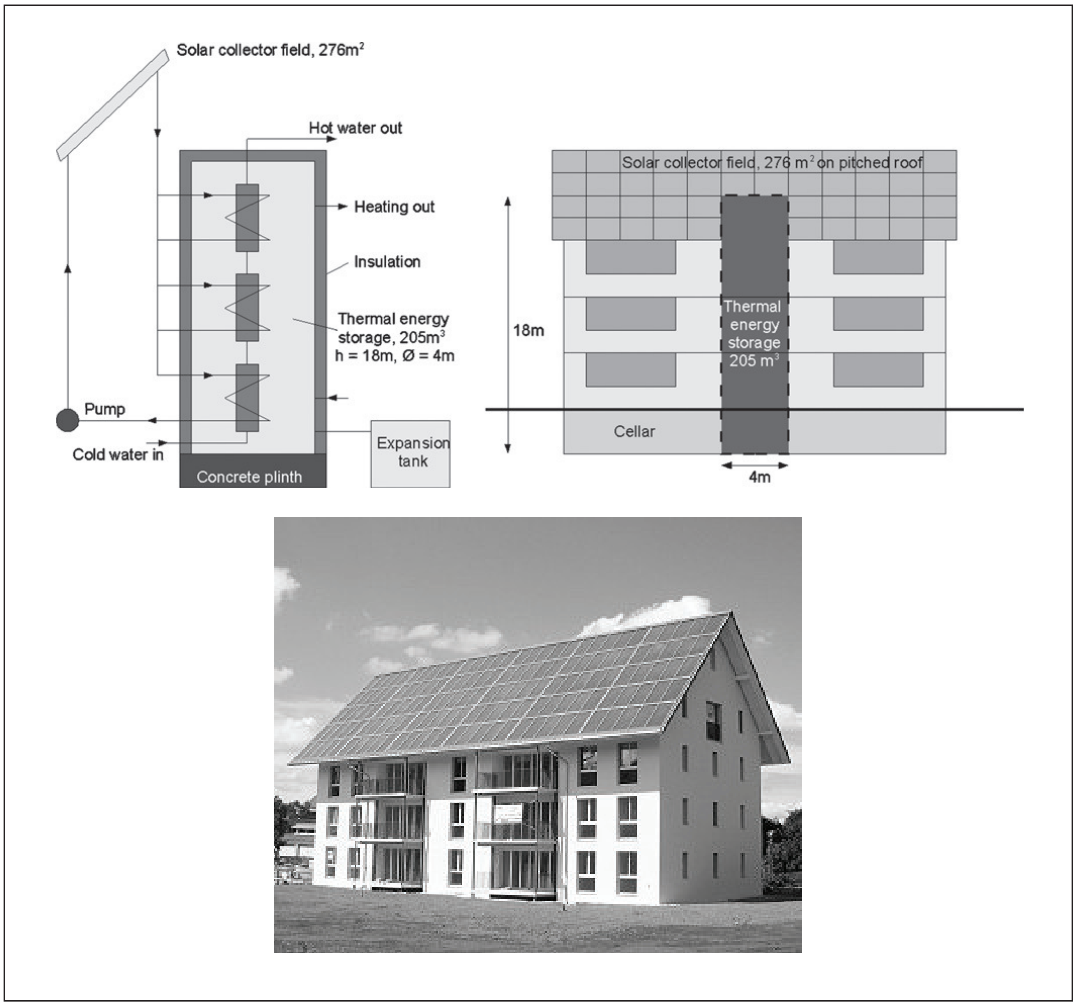

Figure 2.8: Schematic (Simons & Firth, 2011) and photograph (Jenni Energietechnik, 2011b) of Swiss Apartment Building with 100% solar fraction solar thermal system.

heating needs. The ability of a material to store thermal energy is primarily a factor of the density and heat capacity of the material[2]. Water has a very high capacity to hold heat but is not as dense as concrete. The relatively high density of concrete allows a given volume of concrete to store more thermal energy than an equal volume of water. Additionally, in many building projects large volumes of concrete are already present, while storage tanks filled with water are an addition to the building systems that would be unnecessary with a conventional, non-solar, heating system. These differences are highlighted by a simplified example of a STS

[2]For a more detailed explanation of density and specific heat and how they relate to the storage of thermal energy refer to Section 3.2.2.4

Table 2.2: Comparison of Solar Thermal Storage in Concrete Slab versus Water Storage Tanks adapted from Soifer & Stickney (2010)

	Water Tank IP Units(SI Units)	Concrete Slab IP Units(SI Units)
Height		0.33 ft (0.10 m)
Cross Section Area		3200 ft^2 (297.3 m^2)
Volume	85.5 ft^3 (2.4 m^3)	1056 ft^3 (29.7 m^3)
Density	62 $\frac{lb}{ft^3}$ (993.1 $\frac{kg}{m^3}$)	120 $\frac{lb}{ft^3}$ (1922.2 $\frac{kg}{m^3}$)
Heat Capacity	5301 $\frac{Btu}{^\circ F}$ (9965.8 $\frac{kJ}{K}$)	25344.0 $\frac{Btu}{^\circ F}$ (55,737.4 $\frac{kJ}{K}$)
Solar Heat	320,000.0 $\frac{Btu}{day}$ (337,617.9 $\frac{kJ}{day}$)	320,000.0 $\frac{Btu}{day}$ (337,617.9 $\frac{kJ}{day}$)
Storage ΔT	60.4 $\frac{^\circ F}{day}$ (33.9 $\frac{^\circ K}{day}$)	12.6 $\frac{^\circ F}{day}$ (6.1 $\frac{^\circ K}{day}$)

designed and installed in a 3200 square foot house by Soifer & Stickney (2010). Table 2.2 shows the difference between the volume, density, and heat capacity for the example. The solar system Soifer & Stickney (2010) used in their example was an array of eight 4 ft by 10 ft flat plate collectors, which they estimate would produce 320,000 Btu (337,617.9 kJ) on a sunny day. The storage capacity for the water storage is based on a ratio of two gallons of storage capacity for each square foot of collector area. This is a typical ratio and results in the storage volume of 640 gallons (85.5 ft^3). The change in temperature of the thermal storage volume, neglecting all losses from the storage, over one day is determined by dividing the solar input for the day by the thermal storage capacity of the water storage tanks and the concrete slab. The resulting temperature increases from Table 2.2 are 60.4 $\frac{^\circ F}{day}$ (33.9 $\frac{^\circ K}{day}$) and 12.6 $\frac{^\circ F}{day}$ (6.1 $\frac{^\circ K}{day}$) for the water storage tanks and the concrete slab respectively. The combination of the much higher volume of the concrete slab and the high density of the concrete allows the same quantity of solar energy to be stored with a much lower change in temperature. The temperature change in the concrete is low enough that it is feasible to utilize the concrete for storage of the solar energy without leaving the range of temperatures comfortable to the occupants of the building. Additionally, the lower storage temperatures allow the solar collectors to operate at higher efficiencies[3] (Soifer & Stickney, 2010). This example is important to the design of a STS for a ZEB school because it illustrates the feasibility of using a component of the building that is structurally necessary

[3]Refer to Section 3.2.2.3 for more detail on collector performance and efficiency.

and thermally massive for storage of thermal energy generated by a STS. This has the potential to lower the investment cost of the STS system while providing the thermal storage capacity to deliver high annual SFs.

3. Technical Background: Design and Simulation of Solar Thermal Systems

3.1 Solar Thermal System Fundamentals

STS's that deliver thermal energy to buildings can provide a wide range of SF's from very small to unity for a variety of building types. The Swiss apartment building and the Drake's Landing STS's presented in Section 2.4 are examples of STS's intended to meet the entire load for one multi-family building and 90% of the load for a group of free-standing buildings, respectively. These two systems are designed to meet substantially different loads and utilize different types of thermal storage, but the basic components of these systems and the system of the case study in this thesis consist of three major subsystems: the collectors, the heat storage system, and the balance of the system (BOS) components. The BOS consists of the pumps, piping, sensors, controller, and other small components necessary to link the collectors and TS to form a functioning STS. The different types of collectors and thermal storage systems that are relevant to the present case study are presented in this section as well as common methods for determining the space heating and domestic hot water loads. Knowledge of this information is necessary to perform a simulation predicting the performance of STS's.

3.1.1 Solar Collectors

The examples in Section 2.4 utilize two different types of flat plat collectors that are typical of large STS's. The Drake's Landing system utilizes typical modular flat plate collectors that are mounted on top of the roof and the Swiss apartment building utilizes collectors that function as the roof surface (Simons & Firth, 2011). These collectors are both forms of flat plate collectors, which are typically composed of an absorber with integral piping for a heat transfer fluid (HTF)[4], a glass cover, and an insulating layer bound by an aluminum frame (Kalogirou, 2004). Figure 3.1 shows the typical construction of a flat plate collector. Additional collector types used in

[4]See section 3.1.3 for a discussion of heat transfer fluids in solar thermal systems.

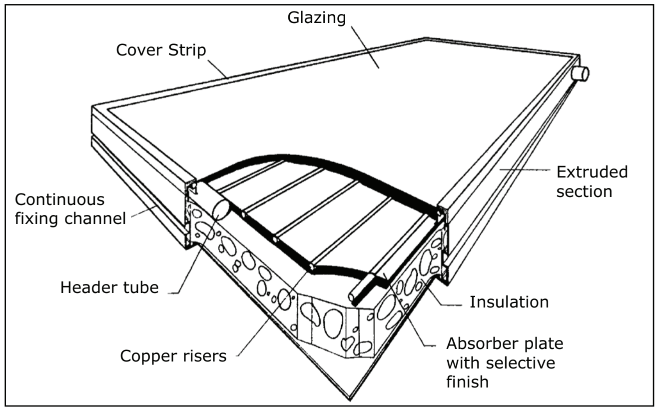

Figure 3.1: Schematic showing typical construction of a flat plate collector (Kalogirou, 2004).

building applications and systems with seasonal storage include unglazed flat plate collectors, evacuated tube collectors, and parabolic trough collectors. Bankston provides data on five solar heating systems with seasonal scale storage that utilize the full range of collectors from unglazed flat plate collectors to parabolic troughs (Duffie & Beckman, 2006, p. 537). Bauer et al. provide a table of 11 systems with seasonal scale storage all of which use a form of a flat plate collector except for one system, which uses evacuated tube collectors (2010). While parabolic trough collectors have been mounted on buildings (Masson, Qu, & Archer, 2007), the high temperatures produced by parabolic trough collectors are not necessary for water and space heating demands. Evacuated tubes utilize vacuum tubes to provide very effective insulation and therefore higher efficiencies than flat plate collectors when the temperature rise above ambient is greater than about 40°C. Figure 3.2 shows the typically construction of two types of evacuated tube collectors. The evacuated tube on the left of Figure 3.2 shows an evacuated tube with a glass to metal connection where the heat pipe exits the evacuated tube. The evacuated tube on the right of Figure 3.2 shows an evacuated tube collector where the vacuum is contained within a double-walled tube. The double-walled tube can provide similar performance to the single walled vacuum tube at a lower cost. Evacuated tubes are typically grouped in banks of 20 or 30 tubes that feed a common manifold. Flat plate and evacuated tube collectors have been studied extensively and models predicting their performance are well developed. Section 3.2.2.3 provides technical information on a thermophysical

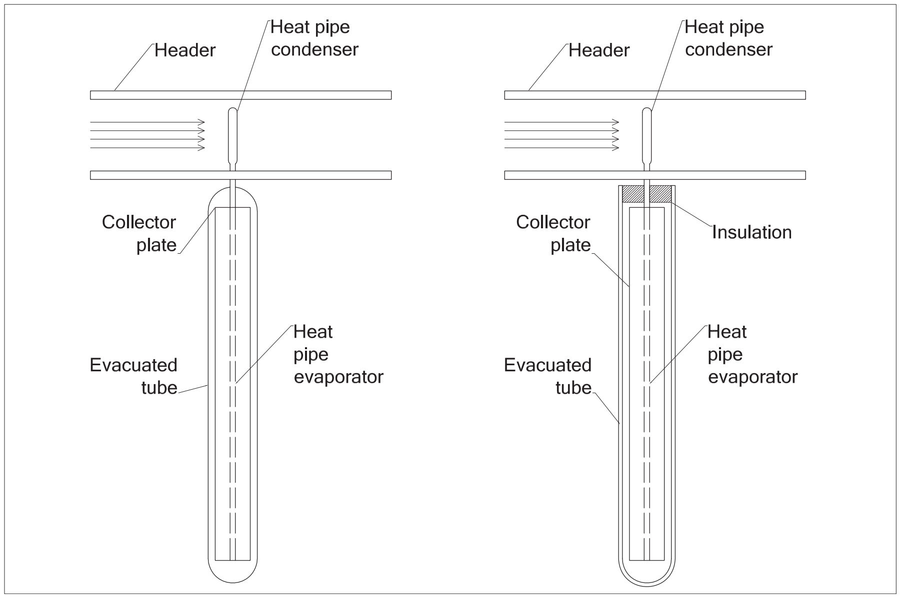

Figure 3.2: Schematic showing typical construction of two types of evacuated tube collectors. Partially adapted from Kalogirou (2004).

model applicable to both flat plate and evacuated tube collectors.

3.1.2 Thermal Storage

Thermal storage (TS) is crucial to the performance of STS's due to the unsynchronized temporal variations in the solar resource and demand for thermal energy to meet building needs. Both solar energy and thermal energy demands of buildings have a predictable and unpredictable component. The variations in the quantity of solar radiation incident on a building surface caused by the motion of the earth relative to the sun are predictable and well understood. However, the quantity of solar radiation that reaches a building surface is also affected by the clearness of the sky, which is less predictable. The consumption of thermal energy by a building may follow predictable patterns, but is ultimately determined by the decisions of the building occupants. Therefore, building energy use can not be predicted with greater certainty than it is possible to predict human behavior. TS systems can be designed to overcome both short, on the order of days, and long, on the order of seasons, mismatches between the supply of solar energy and the demand for energy. The first two examples of STS's in Section 2.4, Drake's Landing and the apartment building in Berne, utilize seasonal scale TS systems, while the third example, the residential building with passive storage, utilizes a diurnal scale TS system. The TS systems in these examples all utilize sensible storage or storage of energy that causes a rise in temperature of the storage medium, which can be 'sensed'. A range of materials can be used for sensible storage. TS systems can also store energy as chemical or latent energy. The capacity and type of thermal storage used with a STS varies widely depending on the type of energy demand, the quantity of the energy demand, the desired solar fraction, the HTF and the size of the collector array.

3.1.2.1 Thermal Storage Strategies

Thermal energy storage relies on the ability of materials to hold energy within their chemical and physical structure in the form of heat. Materials used for TS that melt or evaporate when enough heat is added to them are known as phase change materials (PCMs). While the material is changing phase, the temperature of the material will remain close to the temperature when the phase change began. The amount of heat required to cause material to change phase is the latent heat. Heat that causes an increase in temperature without a change in phase in referred to as sensible heat. The latent heat of fusion refers to the energy required to cause a material to shift from a solid to a liquid or the amount of energy released when a material changes from a liquid to a solid. Similarly, the latent heat of evaporation refers to the shift from liquid to vapor or from vapor to liquid. Latent heat is typically denoted by the greek symbol λ and given in the SI units of kJ/kg. Figure 3.3 illustrates the difference between sensible and latent heat. The change in temperature of material as heat is transferred into or out of the material is determined by the specific heat of the material (C_p) and given in units of $kJ/(kg * K)$. Because both of these units are dependent on the mass of the material it is important to consider the density (ρ), the mass within a given volume, of the material in addition to its specific heat and latent heat. The density of a material in SI units is kg/m^3. The product of the specific heat of a material and its density is the amount of energy that can be stored in a cubic meter of material per degree Kelvin, while the product of the latent heat of a material and its density is the quantity of energy necessary

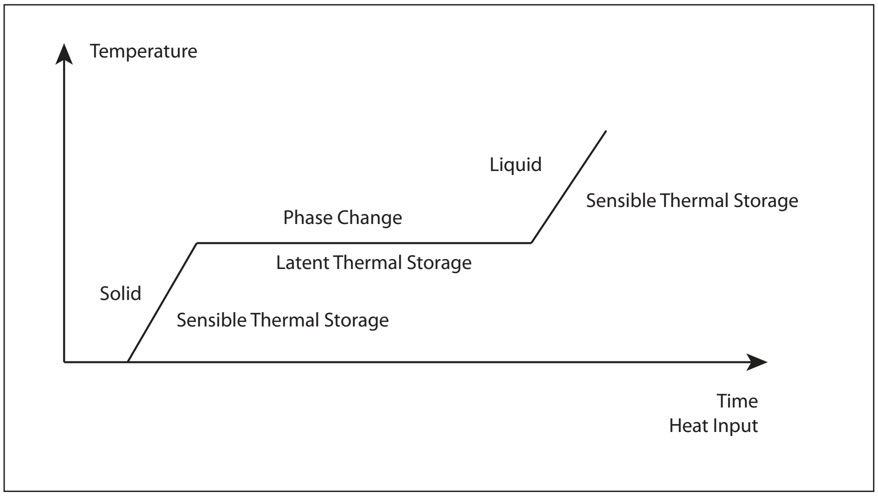

Figure 3.3: Latent and sensible heat.

to cause one kilogram of the material to change phase. Depending on the physical constraints of the thermal storage, the quantity of heat that can be stored in a unit volume may or may not be more important than the quantity of heat that can be stored in a unit of mass. If the thermal storage is on a roof or upper story of a building, it may be more important to store as much heat in the lowest amount of mass as possible to decrease structural requirements. However, if the storage is situated in a ground floor equipment room with limited floor area, it may be more important to decrease the volume required by the thermal storage.

In addition to latent and sensible energy storage, thermal energy can be stored chemically by maintaining stores of the reactants and products of a reversible chemical reaction. Potentially useful reactions include sorption reactions that "store energy by using it to break the bonding of water with a relevant substance (desorption), evaporate one of the products, and condense it for future use" (Pinel, Cruickshank, Beausoleil-Morrison, & Wills, 2011). Chemical storage has great potential, particularly for seasonal storage, due to its high energy density and low stand by losses, but requires further research to be economically and practically viable (Pinel et al., 2011).

Although chemical and latent energy storage can provide greater energy densities and potentially lower stand-by losses than sensible energy storage, they require more complex systems and the storage materials themselves are not as readily available as sensible storage materials. Also, seasonal scale TS systems require very large quantities of energy storage materials making sensible energy storage materials that are available on a building site or easily obtained at low cost preferable. All systems presented in Bauer et al. (2010) utilized a form of sensible TS.

3.1.2.2 Materials for Sensible Storage

Pinel et al. (2011) identify a range of materials and methods for utilizing sensible storage at the seasonal scale. Due to its high density, high specific heat, abundance, low cost, and high level of safety, water is often used as the primary storage medium and frequently used as a HTF in systems that use other materials as the primary storage medium. Large insulated containers filled with water and aquifers both use water as a medium for sensible TS, while rock bed storage and ground storage employ these materials for sensible TS because of their availability and high densities.

TS systems that utilize water as the primary storage medium can be constructed from a variety of materials including steel and concrete or they can make use of natural geologic features, like caverns (Pinel et al., 2011). Due to the temperature difference between the water in TS system and the surroundings, insulation is necessary to reduce heat losses. Insulation of sensible TS is particularly important for seasonal scale storage systems, which have large surface areas contributing to heat losses and must maintain elevated temperatures over many months.

Sensible stores using water typically employ a heat exchanger between the HTF in the collectors and the water in the storage vessel. The most common heat exchanger types are the immersed coil, external tube and shell, and mantle-heat exchangers (Han et al., 2009). Diagram 3.4 shows these types of heat exchangers. The immersed coil heat exchanger is simply a tubular coil placed in the storage tank, which contains the HTF fluid circulating to and from the collectors. In the very large vessels used for seasonal scale TS multiple immersed coils at varying heights can be used to control thermal stratification[5] (Simons & Firth, 2011). The external

[5]Thermal stratification is the separation of hotter and more buoyant water at the top of the storage vessel. This phenomenon and its effect on the performance of STS's is discussed more thoroughly in section 3.1.2.3.

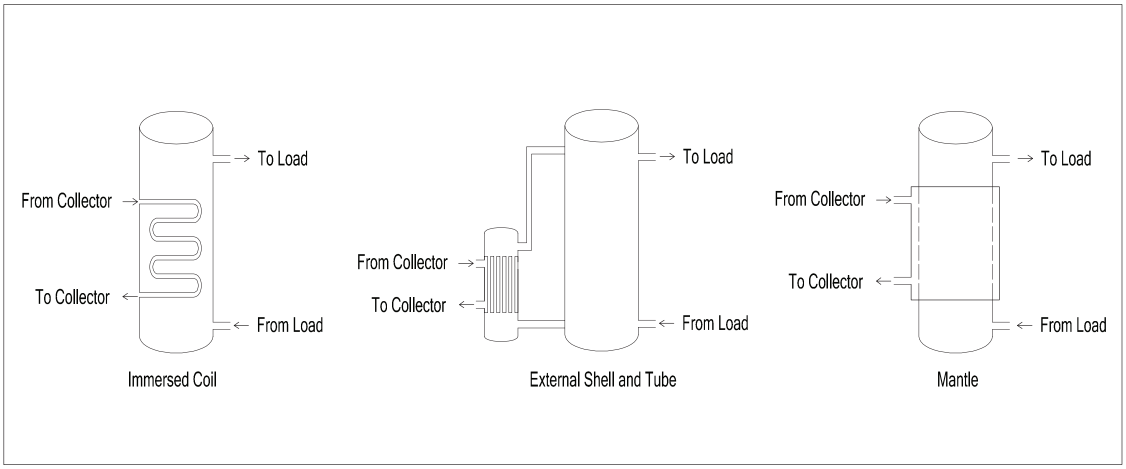

Figure 3.4: Diagram of heat exchangers commonly used in solar thermal systems adapted from Han et al. (2009).

shell and tube heat exchanger consists of a bundle of tubes through which either the collector HTF or the storage water circulates surrounded by a shell that the other fluid flows through over the tubes. The mantle heat exchanger simply consists of a secondary tank surrounding a portion of the main storage tank. HTF is circulated through the void between the two tanks. The internal coil and shell and tube heat exchangers are widely used designs that can be scaled to a wide range of STS. The mantle heat exchanger is less common, but can perform well due to the large surface areas involved (Han et al., 2009).

Aquifer TS requires a site with access to an underground reservoir of water that can be heated without detriment to the ground water. Thermal energy is stored in the aquifer by extracting water, heating it in a heat exchanger, and returning it to the aquifer (Pinel et al., 2011). A STS with aquifer seasonal storage was built in Germany in 2000. The TS is limited to a relatively low maximum temperature of 50 C° due to the potential for altering the ground water chemistry. For this reason, a heat pump was designed to utilize more of the heat stored in the aquifer (Bauer et al., 2010). The necessity for access to a suitable aquifer limits the applicability of this type of TS.

Concrete can be used as a sensible storage medium. The final example presented in Section 2.4 demonstrates how concrete can be used as a replacement for water as a sensible storage medium for a diurnal scale TS system. Concrete has not been used as the primary storage medium in seasonal storage systems due to the relatively higher cost compared to water or ground storage. However, many buildings already require large volumes of concrete in their foundations. Foundations are not geometrically ideal for TS due to the large surface area for heat transfer and the low maximum operating temperature due to their proximity to conditioned building spaces. If these issues could be overcome concrete foundations with their large volumes and high densities could potentially function as a component of a seasonal TS system.

A bed of rock or other material can be used to store thermal energy. Duffie & Beckman (2006) identify these systems as packed beds, pebble beds, or rock piles. A HTF is circulated through the bed to add or remove thermal energy. In diurnal scale systems air is the more commonly used HTF (Duffie & Beckman, 2006), while in seasonal storage systems it is more common to use water (Schmidt, Mangold, & Muller-Steinhagen, 2004). Of the 11 systems tabulated in Bauer et al. three of them use a gravel-water TS system ranging in size from 1,500 m^3 to 8,000 m^3 (2010). Due to the lower specific heat of rock compared to water, a gravel-water TS system requires approximately one and a half times the volume to obtain the same thermal capacity as a water TS system (Schmidt et al., 2004).

Thermal energy can be stored directly in the ground using the rock or soil as the thermal storage medium. These systems are known as either duct TS (Schmidt et al., 2004) or borehole TS (Bauer et al., 2010). The thermal energy can be transferred into the ground through u-tube or annular pipes inside of boreholes drilled into the ground or through horizontal pipes buried in the ground (Duffie & Beckman, 2006). The Drake's Landing STS described in Section 2.4 utilizes a borehole thermal energy system with a 144 boreholes plumbed in series of 6 (Sibbitt et al., 2007). These type of systems can be built to provide very high capacities of TS. Bauer et al. (2010) describe a system constructed and operating in Neckarsulm, Germany that has a borehole TS system with a volume of 63,000 m^3. The viability of the ground thermal storage depends on the geology of the site. Ground conditions resulting in high drilling costs or low specific heat make ground TS less viable.

Water sensible storage is the only form of sensible storage that can be simultaneously charged and discharged. Aquifer, concrete, rock bed, and ground TS systems typically utilize smaller tanks of water to accommodate non-seasonal mismatches between supply and demand (Bauer et al., 2010). The focus for the case study of this thesis will be on water tank storage as this type allows for well-controlled boundary conditions and can be used to establish a range of storage capacities appropriate to the climate, load, and collector area of the case study.

3.1.2.3 Tank Geometries

Thermal stratification occurs in volumes of water used for TS when water of different temperatures separates due to the lower density of hotter water. Thermal stratification in the water tanks of STS can significantly increase the annual SF achieved by the system (Duffie & Beckman, 2006). Therefore, it is desirable to use water tanks with geometries that facilitate thermal stratification. This design goal is in partial conflict with the need to minimize the surface area (SA) to volume ratio (SA:V)[6]. A sphere has the lowest SA to volume ratio, but is impractical for TS. A cylinder provides the lowest SA:V ratio in a practical shape. If heat loss to the surroundings is the most important factor, the ideal ratio of the height of a cylinder to the diameter (H/D-ratio) is one (International Energy Agency, 2005). However, if the effects of stratification are considered then a H/D-ratio between 1-3 is optimal. The effects of stratification are taken into account when considering the geometry of the TS for the thesis, but the benefits of stratification are not considered in the calculations to determine the heat loss from the TS or the annual SF of the STS. This assumption simplifies the simulations and provides conservative results.

3.1.2.4 Insulating Sensible Storage Water Tanks

TS systems are insulated to prevent the loss of the stored heat to the surroundings of the storage tank. Thermally insulating materials are those that have a low thermal conductivity (k). The thermal conductivity is a measure of the rate at which heat is transferred through a material in the presence of a temperature gradient as a function of the length of the material and has the units W/mK in SI

[6]Larger surface areas increase the heat losses from the thermal storage. For the explicit relationship refer to section 3.2.2.4.

notation. TS for residential scale solar thermal systems is typically water contained in an insulated steel tank. A typical tank of this type has 47 mm of fiberglass insulation with a thermal conductivity of 0.036 W/mK (Cruickshank & Harrison, 2010). As the size of the TS and desired storage time increases, the thickness of insulation also increases. The TS for the apartment building in Berne, Switzerland described in Section 2.4 has insulation that is approximately 0.4m thick (Jenni Energietechnik, 2011a). Polyurethane insulation is often used with commercially produced solar thermal tanks and has a thermal conductivity of about 0.02 W/mK (The Engineering Toolbox, 2011). When dealing with multiple layers of different materials, for instance the steel wall of storage tank and the insulation, it is necessary to calculate their combined effect on the rate of heat transfer from the thermal storage medium to the surroundings, typically air. This combined effect is the U value. Rather than adding insulation to the outside of a tank, water stores are often buried or partially buried to reduce heat losses. This approach has been shown to be more effective than insulating an above ground tank for a range of storage sizes from diurnal to seasonal scale (Pinel et al., 2011).

3.1.3 Balance of System Components

Most STS are controlled using a simple differential controller. Sensors measure the temperature near the outlet of the collector and near the bottom of the thermal storage and if the difference between these temperatures is equal to or greater than a set value, typically 7-10 °C, the circulation pump will be switched on (Kalogirou, 2004). When the temperature difference between the collector and storage drops below a set value, typically near 3-5 °C, the pump is switched off. This control scheme avoids circulating HTF through the collector when the radiation incident on the collector is insufficient to add energy to the thermal storage. Additional control is often implemented to avoid overheating of the thermal storage and to prevent HTF from freezing in the collectors (Duffie & Beckman, 2006). The control of seasonal scale STS can become more complicated due to the addition of buffer stores, however the basic logic of the collector operation remains the same.

Solar thermal collectors are joined with the thermal storage systems through piping or ducting and radiation absorbed by the solar collectors is transferred to the load or TS by a HTF, typically water or air. The HTF can be circulated by pumps or fans, forced circulation, or by buoyancy forces. The means of circulation and types of STS are discussed in section 3.1.4. At temperatures below 100 °C, distilled water is the most commonly used HTF due to its high heat capacity, low price, and safety. Propylene glycol is often added to the water to form a non-toxic solution with a depressed freezing temperature. In seasonal scale STS water is typically the primary HTF in the collector loop.

3.1.4 System Types

Figure 3.5 shows the most common types of solar thermal systems. Systems (a) and (b) are known as direct systems because the HTF in the collectors is the same as the fluid in the storage tank. This type of system is only possible when water is used as the thermal storage medium. The systems shown in (c) and (d) are indirect systems because the HTF in the collector is separated from the rest of the system by a heat exchanger. The system shown in (c) employs an internal coil heat exchanger and the system shown in (d) uses an external heat exchanger. The system shown in (d) utilizes two tanks, one for thermal storage only and one with an auxiliary heater source. Another option is to have an external auxiliary heat source as shown in system (b). The system shown in (a) is a thermosyphon system, which relies on the buoyancy of the water heated by the collector to drive the circulation of the HTF. This system requires that the TS be above the collector and is therefore not practical for seasonal scale systems. The other systems rely on pumps to circulate the HTF fluid through the collectors. The system shown in (b) is simple and effective, but is susceptible to damage from water freezing in the collectors. This can be prevented in systems with heat exchangers by the addition of glycol to the HTF to reduce the freezing point. Seasonal scale systems are almost always in areas with freezing temperatures and are generally large scale variations on the systems shown in (c) and (d).

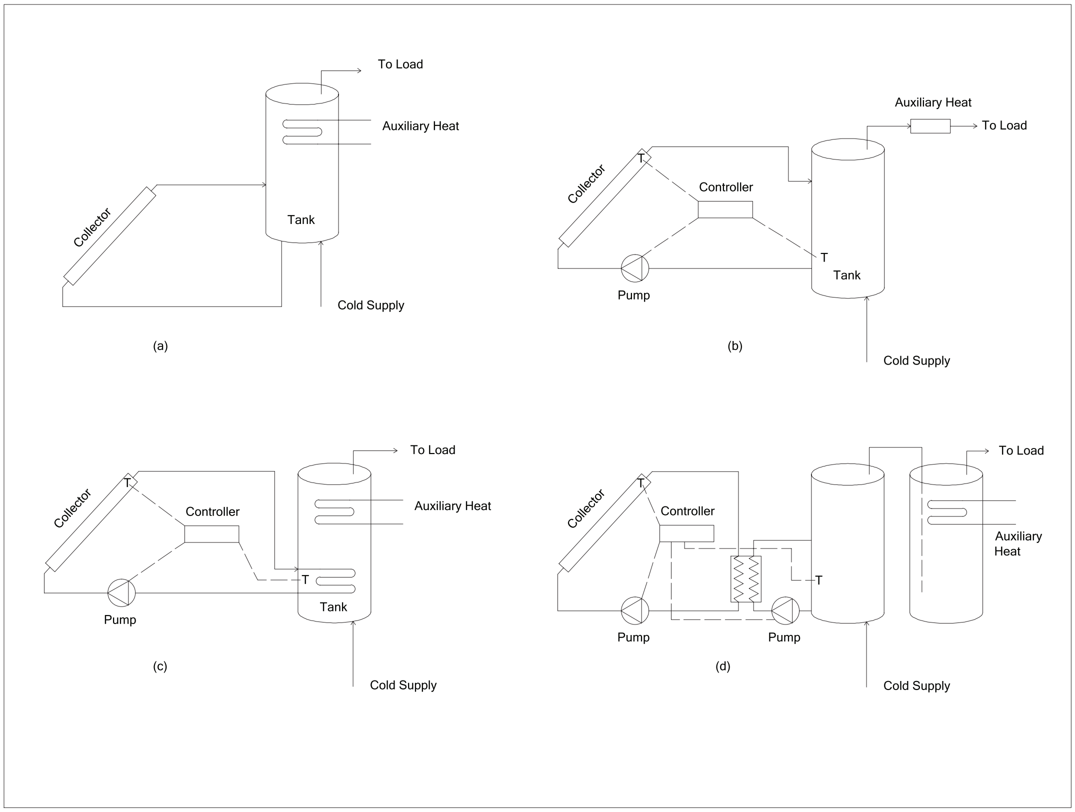

Figure 3.5: Schematics of common solar thermal systems. (a) Thermosyphon system. (b) Active direct system. (c) Active indirect system with internal heat exchanger. (d) Active indirect with external heat exchanger. Schematics adapted from Duffie & Beckman (2006).

3.1.5 Solar Thermal System Loads

The heat produced by solar thermal systems can be utilized to meet energy demands in buildings for space heating and domestic water heating. Additionally, through adsorption or absorption cycles thermal energy can be utilized to produce cooling for buildings. The time-varying nature of both thermal energy available from solar radiation and the cooling, heating, or hot water demands is of vital importance. Each of these building demands has a different profile over time and requires different quantities of heat at different temperatures. For an existing building the demand for hot water can be determined by measuring the temperature and quantity of the water delivered to the water heating equipment. For new buildings the expected quantity of energy required for water heating must be estimated based on the number of expected building occupants, the number and type of equipment that require hot water, and the temperature of the water supplied to the building. Maximum hourly, maximum daily, and average daily hot water use values for various building types that can be used for estimating the quantities of hot water required for a building per person have been developed through studies of water use in existing buildings and are available in the *ASHRAE Handbook: Heating, Ventilating, and Air-Conditioning Applications*, Chapter 49 Service Water Heating. Unfortunately, these values are based on data collected from older buildings that do not have water conserving fixtures or modern appliances with water conservation features (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2007). The number of building occupants is typically specified by the architect based on input from the client or determined based on occupancy of existing buildings with similar program. Knowing the building program and the expected building occupancy, an estimate of the demand for hot water can be made based on the tabulated values provided in the ASHRAE handbook. To determine the energy needed for hot water heating, it is also necessary to know the difference (ΔT_{hw}) between the temperature of the water supplied to the building (T_{mains}) and the temperature required by the demands for hot water, or the setpoint temperature ($\mathrm{T}_{set,hw}$). This temperature difference typically varies throughout the year as the temperature of the water supplied to the building varies with the change in the ground temperature. Burch & Christensen (2007) have developed a correlation for estimating the temperature of water supplied to buildings based on the annual average ambient outdoor temperature and the maximum difference between the monthly average outdoor temperatures, which is presented in Section 3.2.2.2.

3.2 Selection and Implementation of a Design Method

3.2.1 Selection of a Design Method

The STS described in Section 3.1 are common designs and a variety of approaches exist to predict the performance of these systems based on information about the STS, the load on the system, and the climate where the system will operate. Relevant design methods include the Utilizability(ϕ) methods and the Utilizability, f-Chart ($\bar{\phi}$, f-Chart) Method. Software developed to study solar thermal systems include WATSUN 2009, SOLCHIPS, MINSUN, EnergyPlus, and the Transient Energy Simulation Tool (TRNSYS). Unlike the other software tools, TRNSYS can simulate a wide range of system configurations and has been expanded to other applications involving transient energy flows including building envelopes and systems. EnergyPlus is a software tool focused on the simulation of building envelopes and systems that can also simulate the performance of STS's. In addition to these software and design methods, researchers studying STS's often develop models using software like MATLAB, Excel with VisualBasic, or Engineering Equation Solver (EES) to perform calculations based on the equations governing the thermophysical behavior of STS's. Not all of these methods and software tools are applicable to all types of solar thermal systems. The advantages and disadvantages of these methods and software are discussed with particular regard to their applicability to the design of a STS integrated within a NZE school in the NYC borough of Staten Island in Appendix A. The various approaches to predicting the performance of STS's are evaluated based on their availability, their capacity for parametric simulations, and ease of implementation.

EnergyPlus is a computer software tool for simulating the flow of energy within buildings. The tool is based on two older similar software tools, Building Load Analysis and System Thermodynamics (BLAST) and DOE-2. These tools were developed in the late 1970s and intended for use by building engineers and architects to assist in the design of buildings and building mechanical systems (U.S. Department of Energy, 2010d). Of the many improvements to the underlying algorithms of BLAST and DOE-2 implemented in EnergyPlus, the addition of renewable energy simulation capabilities is most pertinent to this thesis (Griffith & Ellis, 2004). The simulation of STS in EnergyPlus is based on the water storage tank models, HVAC connection methods, and the collector performance equations in Duffie & Beckman (2006), which are described in Section 3.2.2.3 (Griffith & Ellis, 2004). Results of STS simulations performed with EnergyPlus have been verified by comparison to TRNSYS simulations (Griffith & Ellis, 2004). EnergyPlus itself is essentially a calculation engine and does not have a graphical user-interface (U.S. Department of Energy, 2010d). Input to and output from EnergyPlus is done with text files, which makes it tedious to work with directly. However, there are many graphical interfaces available from third party developers that simplify creating input for EnergyPlus and analyzing the output. In addition to the graphical interfaces there is a wide-range of programming languages that can be used to automate the process of manipulating text based files. For parametric simulations EnergyPlus includes a parametric preprocessor, which can expand a single input file into multiple files for parametric simulations (U.S. Department of Energy, 2010c). Unlike many of the other software tools for studying the performance of STS's EnergyPlus is readily available, free, and undergoing active development. Due to the accessibility and ability to perform detailed parametric simulations, EnergyPlus was selected for simulating the performance of the STS's under consideration in this thesis.

All of the possible ways of predicting solar thermal system performance are limited by the availability of accurate inputs and the ability of the designer to make reasonable assumptions and implement the simulation or design method without errors. The validity of a prediction of solar thermal system performance can be confirmed through measurements of the performance of actual systems or through comparison with an already validated method. The software tool selected for application in this thesis has been validated through comparison to other previously validated simulation software. The simulations and methods described in this section are based on fundamental knowledge of thermal systems and do not account for many factors that could reduce the performance of an installed system, including the quality of the installation, degradation of performance over time, changes in weather patterns, maintenance of the system, and changes in the building energy demands. Design decisions for both buildings and solar thermal systems based on predictions of solar thermal system performance must be made with awareness of the limitations of these analysis tools. The actual performance of STS designed to achieve high SFs using seasonal storage will be dependent on annual or multi-year weather patterns. The weather files described in Section 3.2.2.1 used with EnergyPlus provide average year data and the simulation results obtained with these files do not provide predictions of performance for periods greater than a year.

3.2.2 Implementation of Selected Design Method

EnergyPlus was selected as the analysis tool for exploring the combinations of collector areas and storage volumes that would provide a large portion of the space and water heating loads of a NZE school in the Staten Island Borough of NYC. The goal of the case study is to determine the range of collector area and storage capacity combinations that would provide reasonable annual SF's. In order to determine SFs for varying collector areas and storage capacities using EnergyPlus, an estimate of the energy loads on the STS is necessary. Additionally, understanding the thermophsyical models of collector performance, thermal storage, and incident radiation implemented in EnergyPlus is necessary to provide appropriate inputs and to extrapolate reasonable conclusions from the simulation results. This section provides a description of the relevant EnergyPlus models and a description of how Unix shell scripts were used to expand the parametric simulation capabilities of EnergyPlus. The specific loads, collector performance parameters, and weather data used to implement the design methods are presented in Section 4 and the results of the design process are presented in Section 5.

3.2.2.1 Utilizing EnergyPlus as a Solar Thermal System Simulation Tool

EnergyPlus version 6-0-0 includes an example input file for simulating a solar thermal system and extensive documentation about all aspects of EnergyPlus. The simulations performed for this thesis utilize a modified version of the example solar thermal system input file. The information required to run an EnergyPlus simulation is contained in an input data file (.idf) (U.S. Department of Energy, 2010c, p.1). In addition to an .idf input file, EnergyPlus requires climatic data about the site contained in a comma-seperated value formatted for EnergyPlus or ESP-r (E/E format) (U.S. Department of Energy, 2010a). The weather files for EnergyPlus are denoted by a .epw extension and are available for many locations. With these two input files an EnergyPlus simulation can be initiated using the EP-Launch program or directly through a Unix command line terminal. The simulations for this thesis were performed by issuing commands from a Unix Bash shell on a computer running the Apple OSX 10.6.8 operating system. Running an EnergyPlus simulation produces a collection of text output files, which include a file containing a list of errors and warnings generated while the simulation is running (.err), a file containing a list of variables that are available for producing output (.rdd), and a .csv file of the variables selected for output (.csv). Variables listed in the .rdd output file can be added or removed from the .idf file to control the variables that are recorded in the output .csv file. An additional text input file with the extension .rvi can be constructed to customize the output that is generated in the .csv file (U.S. Department of Energy, 2010c, p. 2182). The .rvi files were used for all the simulations to limit the output to a few important variables necessary for assessing the validity of the simulation and calculating the SF.

The .idf input files are text files that can be edited in any text editor. They contain the information necessary to describe the physical systems simulated and information to control the simulation. The information in the .idf files is grouped into objects, which are separated by semicolons. Each object provides the parameters required by EnergyPlus to implement the model of the component described into the simulation. The .idf files used in this thesis include objects that describe the major components of a STS, the solar system controls, and the loads on the system. The models used by EnergyPlus to simulate the performance of each of these major STS components and the methods for determining the necessary inputs are described in this section. The methodology for calculating the loads on the STS are described in the next sub-section followed by a description of the thermophysical models used by EnergyPlus to simulate the performance of the solar collectors and storage tanks.

3.2.2.2 Methods for Estimating Solar Thermal System Loads

To determine a SF for a given STS using EnergyPlus it is necessary to specify information about the quantity of energy required and how the demand for energy is distributed temporally. There are a variety of ways to specify both water heating and space heating energy needs in an EnergyPlus .idf file. In EnergyPlus, the energy required to meet the building space heating demand can be calculated based on information provided in the .idf about the physical construction of the building and schedules for its use. Similarly, the water heating demand can be calculated based on individual fixtures and schedules describing their use. To keep the simulation limited to the performance of the STS the loads used in this case study are calculated and imported into EnergyPlus using an EnergyPlus “LoadProfile:Plant” Object. The “LoadProfile:Plant” object utilizes hourly data specified by two “Schedule:File” objects, which import values for the plant mass flow rate in m^3/sec and the plant power demand in watts from .csv files. The building space heating loads used in the simulations of the STS's were obtained from an eQuest model provided by the company designing the building systems for the net-zero energy school. Water heating loads (L) can be calculated as

$$L = m_{hw} C_{p,water} \Delta T_{hw} \tag{3.1}$$

where,
m_{hw} = mass of the hot water demand for the hour (kg)
$C_{p,water}$ = the specific heat of water (j/kgK), and
ΔT_{hw} = $T_{set,hw}$ - T_{mains} (K)

Estimates for the quanity of water required can be based on ASHRAE data or measured data as described in section 3.1. The temporal distribution of the hot water demand can be based on either measured data for a retrofit system or on predictive estimates of the water use. The specific heat of the water is dependent on the temperature and can be found readily as tabulated data (Duffie & Beckman, 2006, p.856). The setpoint temperature is determined by the type of demand for hot water. Burch & Christensen (2007) have developed a correlation for estimating T_{mains} based on the annual average ambient outdoor temperature and the maximum difference between the monthly average outdoor temperatures. These values are easily determined by processing the temperature data available in weather files created for simulating building energy flows. The correlation as implemented in EnergyPlus is

$$T_{mains} = (T_{amb,avg} + 6) + ratio * (\frac{\Delta T_{out,maxdiff}}{2}) * sin(0.986 * (day - 15 - lag) - 90) \tag{3.2}$$

where,

$T_{amb,avg}$ = the annual average outdoor air temperature (° F)

T_{mains} = the water mains temperature (° F)

$T_{out,maxdiff}$ = the maximum difference between monthly average ambient temperatures(° F)

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

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

Each hour of the day is given the same value for T_{mains}. This simplification does not have a strong effect on the results because the change in T_{mains} each day is relatively small. With knowledge of the volume of hot water required each hour Equation 3.1 can be used to calculate hourly values for the energy required for water heating. These calculated values can be used as inputs to an EnergyPlus simulation.

3.2.2.3 Modeling Solar Thermal Collector Performance

Models of solar thermal collector performance are necessary for estimating the performance of a STS and determining annual SFs. Models of flat plate solar collectors and evacuated tube solar collectors are well developed and tested and range from detailed models requiring knowledge of the details of the collector construction and the physical properties of the materials used in the collector to models with two or three parameters describing collector performance that are determined through physical testing. The simpler two to three parameter models often provide sufficient accuracy for estimating the performance of STS that provide energy to water and space heating needs. This type of model is implemented in EnergyPlus as described in this section (U.S. Department of Energy, 2010b, p. 893).

The useful heat gained from a solar collector (Q_u) can be determined from

$$\dot{Q}_u = A_c F_R[S - U_L(T_i - Ta)] \tag{3.3}$$

where,

A_c is the area of collection surface,

F_R is the ratio of actual heat transfer to the maximum possible heat transfer,

$S = G_T(\tau\alpha)_{av}$,

U_L is the overall heat loss coefficient,

T_i is the inlet temperature to the collector and

T_a is the ambient temperature. (Duffie & Beckman, 2006, p. 265)

In Equation 3.3 G_T is the irradiance on a tilted surface, which is determined with a sky model by EnergyPlus. EnergyPlus utilizes the Perez sky model to calculate the beam, diffuse, and ground reflected radiation incident on a tilted surface, in this case the collector surface (U.S. Department of Energy, 2010b, p. 126). $(\tau\alpha)_{av}$ is the average transmittance absorptance product, which is further explained in this section. Duffie & Beckman (2006, p. 266) describe Equation 3.3 as the "most important equation in *Solar Engineering of Thermal Processes*". Equation 3.3 is truly an elegant mathematical description of the parameters affecting the useful quantity of energy available from a flat plate or evacuated tube solar collector. Combining Equation 3.3 with the equation for the efficiency (η) of a flat plate collector

$$\eta = \frac{Q_u}{A_c G_T} \tag{3.4}$$

,which is the useful gain from the collector divided by the total energy received by the collector surface, and simplifying gives

$$\eta = F_R(\tau\alpha)_{av} - F_R(U_L)\frac{T_i - T_a}{G_T} \tag{3.5}$$

The efficiency of a flat plat solar collector can also be written as

$$\eta = \frac{\dot{m}C_p(T_o - T_i)}{A_c G_T} \tag{3.6}$$

where,

$\dot{m}$ is the mass flow rate of HTF through the collector,

C_p is the specific heat of the HTF and

T_o is the temperature of the HTF fluid at the outlet of the collector.

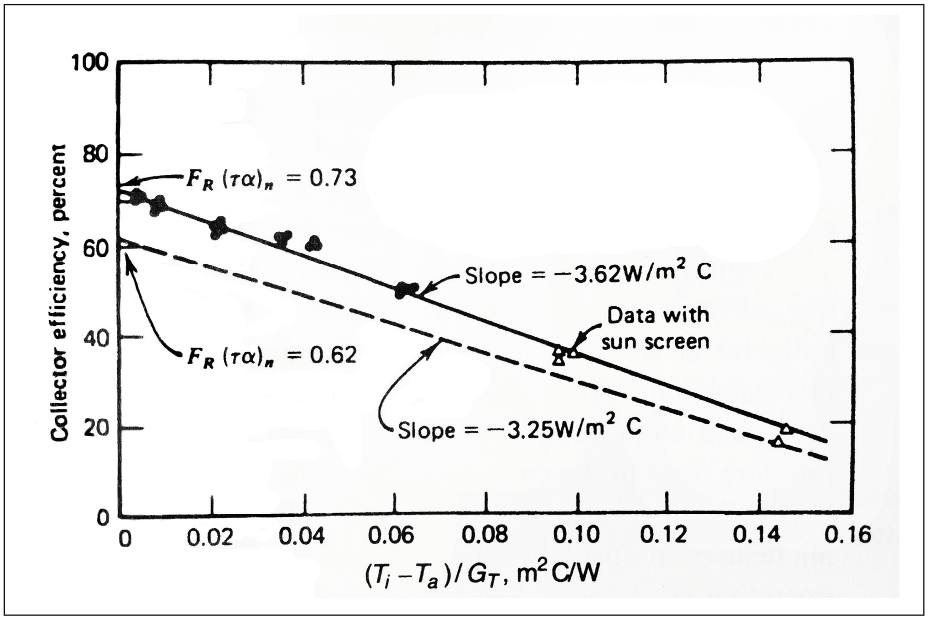

Figure 3.6: Collector Efficiency versus ratio of the difference between the inlet and outlet temperature to the irradiation on the tilted surface for a liquid solar collector. (Duffie & Beckman, 2006, p.301)

The variables in Equation 3.6 are either readily available material properties (C_P) or can be easily measured through a physical experiment. The Solar Ratings and Certification Corporation (SRCC) publishes the results of experiments performed on commercially available solar thermal collectors by an independent laboratory as part of the their OG-100 collector certification (Solar Rating and Certification Corporation, 2011a). The results of these experiments are typical graphed with the efficiency on the ordinate and the ratio of the difference between the inlet and outlet temperature to the irradiation on the tilted surface ($T_o - T_i/G_T$) on the abscissa. A line is fitted to the data points as shown in Figure 3.6. The values of $F_R(\tau\alpha)$ and $F_R(U_L)$ from Equation 3.5 can be extrapolated from the y-intercept and the slope of the line fitted to the test data. These values can then be used in the collector model to determine the efficiency and the usable energy produced by the collector. The extensive library of test data available on the SRCC website allows simulating the performance of a wide range of commercially available collectors (Solar Rating and Certification Corporation, 2011b).

The third parameter of the collector model, in addition to $F_R(\tau\alpha)$ and $F_R(U_L)$, is the incidence angle modifier ($K_{\tau\alpha}$ or IAM), which adjusts the $F_R(\tau\alpha)$ parameter to account for the reduction in the value of $\tau\alpha$ when the incident radiation is not perpendicular to the surface of the collector. The incident angle modifier as a function of the incidence angle of beam radiation is

$$K_{\tau\alpha}(\theta_b) = \frac{(\tau\alpha)_b}{(\tau\alpha)_n} \tag{3.7}$$

Souka and Safwat developed a general expression for the IAM as a function of the angle of incidence (θ) and a constant known as the incidence angle modifier coefficient (b_o). For flat plate collectors the IAM can be determined with a value of b_o and θ from

$$K_{\tau\alpha} = 1 - b_o\left(\frac{1}{cos\theta} - 1\right) \tag{3.8}$$

Values for b_o are determined by physical testing of the collectors. SRCC follows the standards of ASHRAE Standard 93 to determine values of b_o (Solar Rating and Certification Corporation, 2011a), which recommend that collectors be tested indoors at incidence angles of 0°, 30°, 45°, and 60° (Duffie & Beckman, 2006, p.298). Evacuated tube collectors can not be characterized by a single incident angle modifier because their tubular profile reflects light differently along the length of the tube than across the width of the tube. The EnergyPlus collector model does not support the use of biaxial IAM's and the Engineering Reference recommends that either the longitudinal or transverse IAM be used with an understanding of the approximate nature of this use (U.S. Department of Energy, 2010b, p. 895). Values for b_o for flat plates and for evacuated tubes can be found with the values of $F_R(\tau\alpha)$ and $F_R(U_L)$ on the SRCC website.

Modifying Equation 3.5 to include the IAM gives

$$\eta = F_R(\tau\alpha)_{av}K_{\tau\alpha} - F_R(U_L)\frac{T_i - T_a}{G_T} \tag{3.9}$$

These three collector parameters combined with knowledge of the climatic conditions from a weather file and the temperature of the HTF are used in EnergyPlus to estimate the quantity of usable energy delivered from the solar collectors to the

STS. The EnergyPlus model of a solar collector requires multiple objects within the .idf file. The parameters describing the performance of the solar collector are defined in a "SolarCollectorPerformance:FlatPlate" object and the connections to the rest of the system are described in a separate "SolarCollector:FlatPlate:Water" object (U.S. Department of Energy, 2010c, p.1364). This allows an array of collectors to be defined without reentering the performance parameters. The quantity of solar radiation incident on the surface of the collector is calculated based on a "Shading:Site:Detailed" object. Each collector defined in the .idf file must have its own shading surface object with the area specified in the "SolarCollector-Performance:FlatPlate" object. Additionally, when defining an array with parallel collectors it is necessary to define a branch for each solar collector and include each branch in a branch list object, splitter list object, and mixer list object.

3.2.2.4 Fundamentals of Thermal Storage and Calculation of Overall Tank Heat Loss Coefficients

EnergyPlus contains objects for modeling fully mixed and stratified tanks containing water to be used for the storage of thermal energy (U.S. Department of Energy, 2010c, p. 749). The inputs of primary importance to this thesis are the volume of the tank and the loss coefficient to the surroundings. The loss coefficient input is described in Equation 3.12 and the volume is simply specified in cubic meters. The effect of heat exchangers between the storage tank and the solar collectors and the storage tank and the load are considered in EnergyPlus through the use of a heat exchanger effectiveness value, which is specified as a decimal number between 0 and 1.

TS systems that are part of STS's providing energy to building water or space heating needs are nearly always at a higher temperature than their surroundings, which causes them to lose heat. If the TS is assumed to have a uniform temperature, the rate of heat lost from the TS to the surroundings is approximately

$$\dot{Q}_{st} = (UA)_s(T_s - T_a') \tag{3.10}$$

where,

$\dot{Q}_{st}$ is the rate of heat lost from the storage,
$(UA)_s$ is the overall heat loss coefficient of the storage (U) multiplied by the surface area of the storage (A),
T_s is the temperature of the storage and
T'_a is the ambient temperature of the storage surroundings (Duffie & Beckman, 2006, p. 709).

Estimating values for Q_{st} is important to the estimation of the annual performance of a STS and requires estimates of the U value, surface area, the temperature of the storage and the temperature of the storage surroundings. The methods used for estimating these values are presented in this section.

Also, important to the design of the STS is the thermal capacity of the storage, which, for sensible storage, is

$$Q_s = (mC_p)_s(\Delta T_s) \tag{3.11}$$

where,
m is the mass of the storage medium,
C_p is the specific heat of the storage medium and
ΔT_s is the difference between the high and low temperatures in one cycle of the STS (Duffie & Beckman, 2006, p. 380).

When dealing with multiple layers of different materials, for instance the steel wall of storage tank and the insulation, it is useful to calculate their combined effect on the rate of heat transfer through the thermal storage medium to the surroundings, typically air. This combined effect is the U value from Equation 3.10 and is the inverse of the sum of the widths of each material layer divided by their thermal conductivities (Incropera, DeWitt, Bergman, & Lavine, 2007):

$$U = \frac{1}{\frac{l_1}{k_1} + \frac{l_2}{k_2} + \frac{l_i}{k_i}} \tag{3.12}$$

Equation 3.12 can be used to calculate U values for a composition of multiple materials, which are useful if the temperatures at the exterior surfaces are known. For this thesis it is assumed that the temperature of the material enclosing the storage medium is at the same temperature as the storage medium. The surface temperature of the insulation is not assumed to be equal to the temperature of the surroundings in the case of a storage tank surrounded by air. The effect of the heat lost from the insulation to the surrounding air is due to convection, which can be accounted for when calculating the U-value by including the convection heat transfer coefficient (h):

$$U = \frac{1}{\frac{l_1}{k_1} + \frac{l_2}{k_2} + \frac{1}{h}} \tag{3.13}$$

Calculation of a single U-value for use in calculating the heat losses from a storage tank is a simplification, but it is the method used by EnergyPlus and provides reasonable results.

3.2.2.5 Utilizing Parametric EnergyPlus Simulations to Determine STS Design Space

To determine the reasonable range of collector area and storage volume combinations a large number of simulations varying both the collector area and the storage capacity need to be performed. EnergyPlus includes a utility program, the ParametricPreprocessor, for these type of parametric simulations (U.S. Department of Energy, 2010c, p. 2131). A special group of objects are defined for use with the ParametricPreprocesor and may be included in an .idf file to create a group of .idf files identical except for changes to parameters specified by the parametric objects. This capability was used to generate simulations of STS with the same collector area, but varying TS capacities and overall heat loss coefficients. The ParametricPreprocessor was well suited to this task since these values are each one line in the object defining the TS. The complexity of defining multiple parallel collectors to form a solar array as described in Section 3.2.2.3 makes it difficult to implement the ParametricPreprocessor to vary the total collector area. Additionally, the case study is for a building with loads that will require a solar array with hundreds of collectors making manual manipulation of the .idf files prohibitively time-consuming. This challenge was overcome by developing a Bash shell script utilizing the text

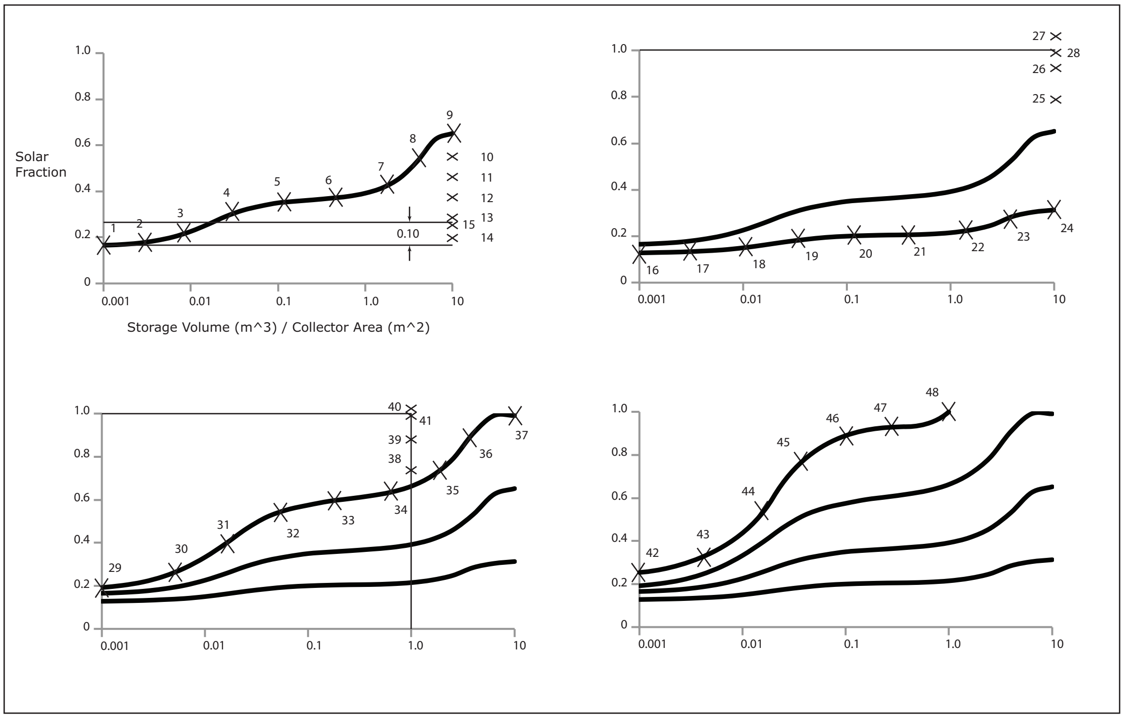

Figure 3.7: Diagram of sequential process of parametric shell script.

editing tools AWK and ED to automate the replication of the objects required in the .idf file to simulate a large collector array.

To further automate the process of determining the combinations of collector areas and storage volumes that would provide reasonable SF's for a given load additional Bash shell scripts were developed to add parametric objects to an .idf file, change the volume and heat loss coefficient of the thermal tank object, and run parametric simulations. These scripts were combined into a single script that will run EnergyPlus simulations of a given range of storage to collector ratios when provided a weather file, an annual load in MWh, a number of parametric simulations to run, a starting storage volume to collector area ratio, and an ending storage volume to collector area ratio. If the solar fractions determined in these simulations are plotted against an abscissa of the storage volume to collector area ratio the results will resemble the dark curves in Figure 3.7. Each curve in Figure 3.7 shows the effect of varying TS capacity for a set collector area and has two relatively flat portions and two relatively steep portions. The flat portions indicate ranges where the performance of the STS is relatively independent of the volume of TS. The flatter areas adjacent to the ordinate denote TS volumes that do not have enough capacity to overcome diurnal mismatches between the available solar energy and the demand for thermal energy, while the second flat region denotes TS volumes that have more than enough storage capacity for diurnal mismatches between supply and demand but not enough to overcome seasonal mismatches. The algorithm implemented in the shell scripts assumes that the results of the simulations will follow the trends shown here, which were originally identified by Braun, Klein, & Mitchell (1980). In Figure 3.7 each 'x' represents one EnergyPlus simulation and the numbers identifying the x's shows the sequence of the simulations. Each curve in Figure 3.7 is created by utilizing the ParametricPreprocessor to generate a set of .idf files that have the same collector area and varying storage volumes with proportionally varying overall heat transfer coefficients and then using EnergyPlus to simulate each input file. Additionally, the starting and ending temperature of the storage tank is checked after each simulation and the simulation is repeated replacing the starting tank temperature for the new simulation with the ending tank temperature of the old simulation if the two values differ more than a defined convergence value. This process is labeled as the Parametric Sequence in Figure 3.8, which shows a flow chart of the script processes. The first collector area is based on a rule of thumb that large solar systems with long-term storage should have 1.25-2.5 m^2 of collector area for every MWh of annual heating load (Hegger et al., 2008, p. 74). The annual load supplied by the user of the script is multiplied by 2 to obtain the collector area for the initial parametric simulation.

The x's aligned vertically in Figure 3.7 show hypothetical results of the process labeled "Seek Solar Fraction" in Figure 3.8. The 'Seek Solar Fraction' process has four different options for implementation. The first option, shown in the upper left graph of Figure 3.7, seeks the collector area that results in a SF that is 0.10 higher than the SF for the original array size at the highest storage volume to collector area ratio. This implementation of the 'Seek Solar Fraction' process attempts to identify an array size that is nearly too small for the given load. The second implementation shown in the upper right graph of Figure 3.7 seeks to identify a collector area that will provide a SF of 1 at the highest ratio of storage volume to collector area. The

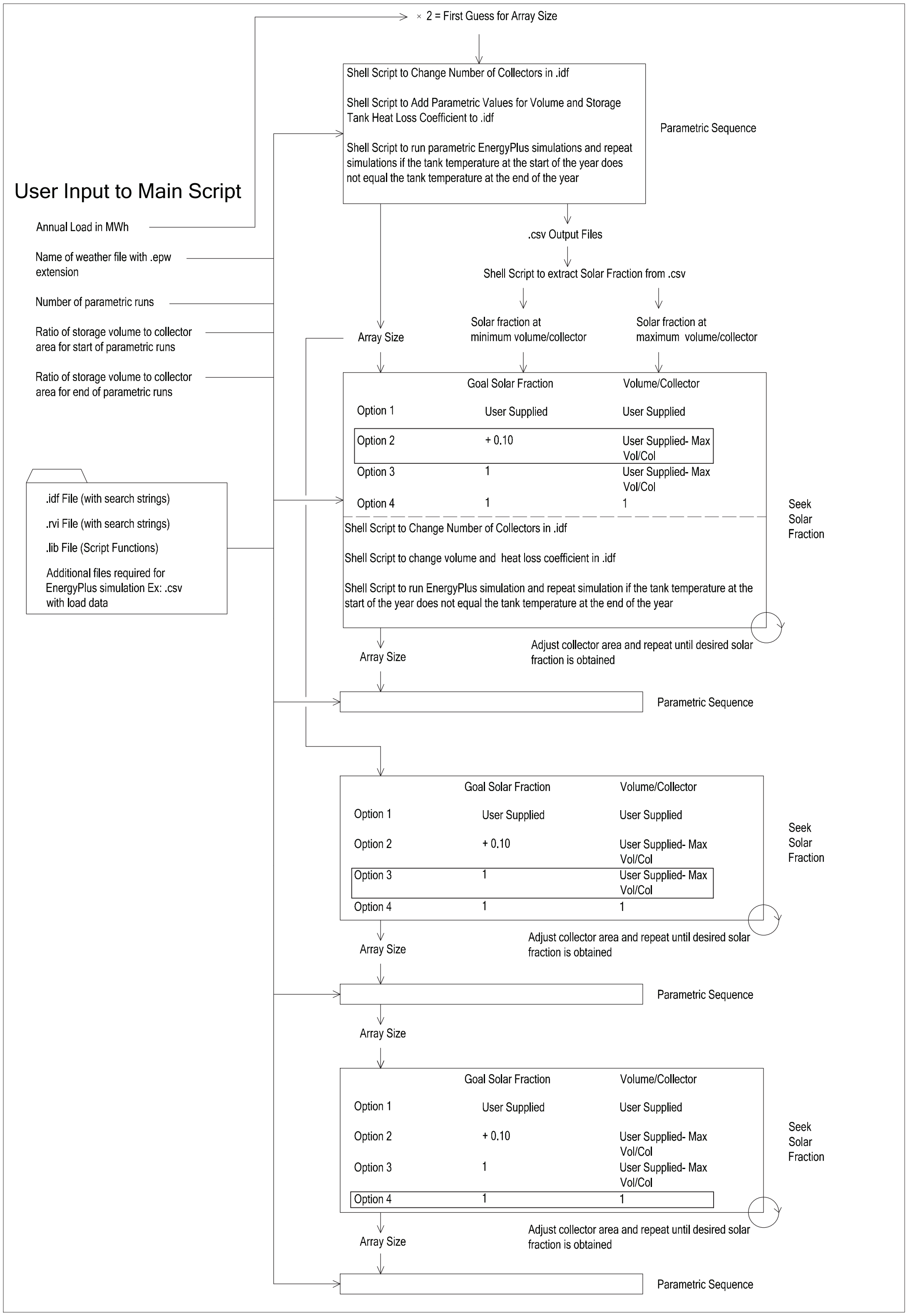

Figure 3.8: Block diagram of shell scripts used to control parametric EnergyPlus simulations.

third implementation shown in the lower left graph of Figure 3.7 seeks to identify a collector area that will provide a SF of 1 at a ratio storage volume to collector ratio of 1.0. The 'Seek Solar Fraction' utilizes a bisection type algorithm to approach the goal SF. A stepsize is initialized that is proportional to the array size and systems with collector areas incremented by the value of the stepsize are simulated until the SF is within a given tolerance of the goal SF or it misses the goal SF. If the goal SF is missed the stepsize is halved, the sign is inverted and the process continues. The Bash shell code is provided in Appendix B.

The result of running these simulations is the data necessary to produce a graph similar to the graph in the lower right of Figure 3.7, but specific to a given load. The specifics of applying these scripts to the case of a net-zero energy school in New York City are considered in the following section.

4. Case Study: Applying Parametric EnergyPlus Simulations to the Design of a Solar Thermal System for a Net-Zero Energy School in NYC

The focus of this thesis is on the application of the algorithm for parametric EnergyPlus simulations described in Section 3.2.2.5 to a case study building. The case study building is a net-zero energy school to be built in the Staten Island borough of New York City (NYC). The school is currently in the design phase and substantial work has been made towards developing a design methodology that can produce a building capable of meeting the net-zero energy goal. As part of the development of the design methodology, the design team, architectural designers and consulting engineers chose the net zero site energy definition for a ZEB, defined in Section 2.3, as a goal of the project. The design team justified this choice based on the ease of evaluating the energy balance of the school through net metering and explaining the site ZEB concept to members of the school community. As noted in Section 2.3 this thesis accepts the design teams decision to use the site ZEB definition.

Figure 4.1 shows a possible photovoltaic array for the school building. This drawing is shown here only to provide a sense of scale of the building to reference when discussing the results of the STS simulations. The total area of the PV array shown here is 1430 m^2. If half of this area were allotted to solar thermal collector area there would be area for 715 m^2 of solar thermal collectors. Unlike the PV system auxiliary equipment, electrical wiring and inverters, a STS requires a large storage volume. This volume could potentially be buried on-site or beneath the building or could be located within the building as in the swiss apartment building from Section 2.4.

The methodology developed by the design team seeks to reduce building energy use through efficiency measures and generate the remaining energy required by the school annually through the use of a large PV array. This approach is essentially prescribed by the definition of a ZEB, but the reliance on photovoltaics as the primary source of on-site renewable energy is not the only option. The project

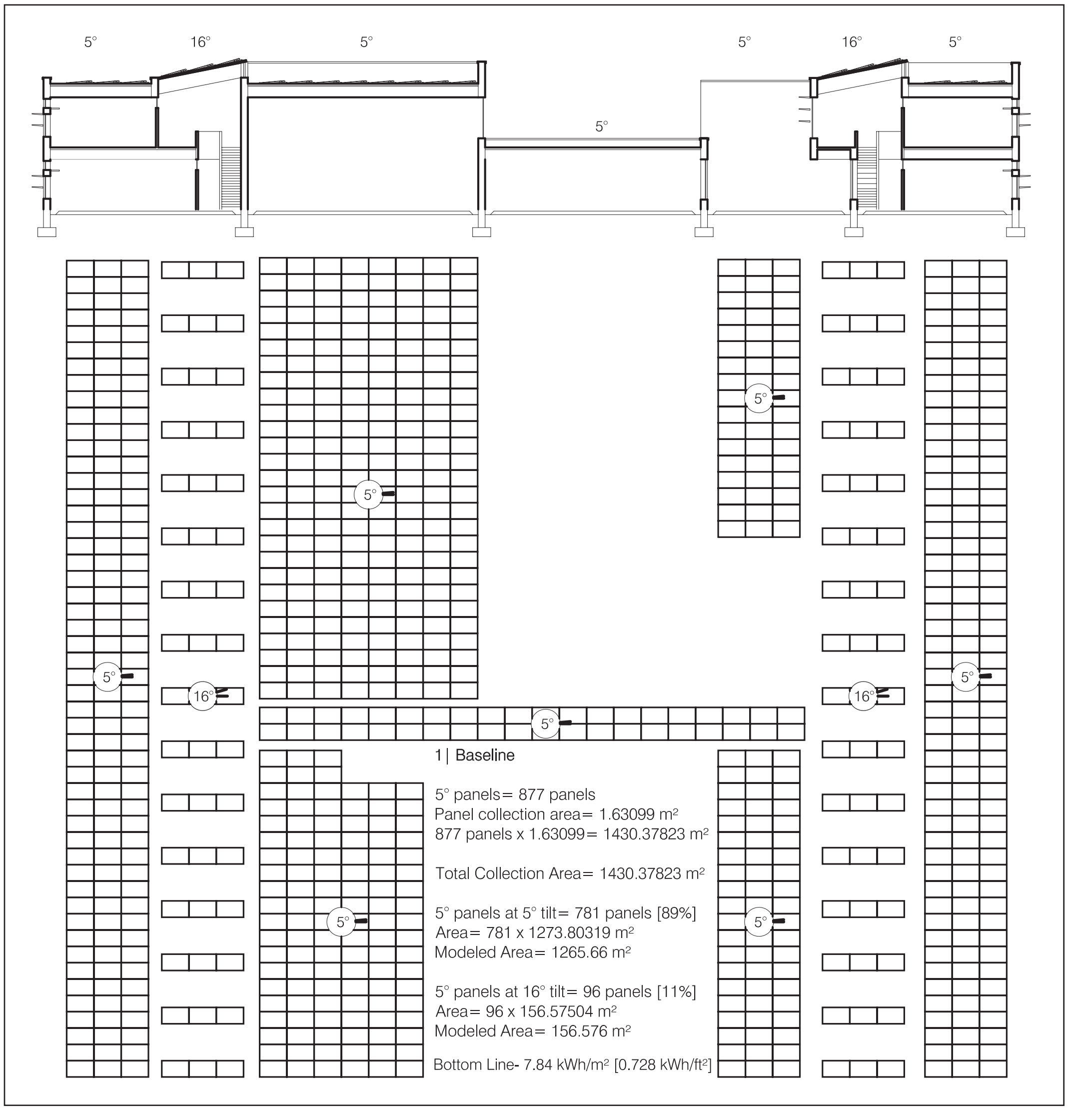

Figure 4.1: Plan and elevation of a potential photovoltaic array for the school building. Drawing for design exercise by Brandon Andow of the Center for Architecture Science and Ecology (CASE), 2011.

includes a STS to meet water heating loads, but it is categorized as one of the efficiency measures. This is likely because there is not a grid available for exporting thermal energy generated by the STS, unlike the electric energy generated by the PV system. The PV system essentially uses the grid as a non-physical form of seasonal storage. There are not electric energy storage technologies that can be implemented cost effectively to store energy generated by the PV system in the summer for use in the winter on site. The examples in Section 2.4 demonstrate the feasibility of storing thermal energy on-site seasonally. The case study analysis utilizes the shell script and EnergyPlus as described in Section 3.2.2.5 to determine a range of collector arrays and storage volumes applicable to the case study loads. To apply the parametric EnergyPlus algorithm from Section 3.2.2.5 values for the parameters of Section 3.2 must be determined. This section describes the process for determining those values and presents the chosen values.

4.1 Simulated System Configuration and Assumptions

The physical components of the STS modeled by the EnergyPlus .idf objects can be combined in a variety of ways to form different types of STS. Figure 4.2 shows the major components organized and labeled by the EnergyPlus conventions for describing system connections. This system is a combination of the active indirect systems with internal heat exchanger and external heat exchanger from Figure 3.5 in Section 3.1.4. The system modeled is an indirect system with a storage tank, internal heat exchanger, and an external source of auxiliary energy. The auxiliary source of energy is a water heater with a very small storage capacity, 0.001 m^3, and a high maximum power input. The auxiliary heater increases the temperature of the HTF in the demand loop to the setpoint temperature, 50°C, if the setpoint temperature has not been reached after the HTF passes through the HX in the storage tank. A tempering valve mixes HTF not heated by the stored solar energy with the heated HTF if the HTF leaves the storage tank HX above the setpoint temperature. The pumps in the system are modeled as variable speed pumps, which will adjust the flow rate in the loops to maintain the inlet and outlet temperatures specified. The system is controlled by two 'AvailabilityManager' objects, which implement the logic of a differential controller as described in Section 3.1.3. The simulated system starts circulating fluid through the collector array when the difference between the temperature at the array and the bottom of the storage tank is 10°C and stops circulation when the temperature difference drops to 2°C. Overheating protection is implemented by the second 'AvailabilityManager' object. A maximum temperature of 98°C is allowed in the storage tank before circulation of the HTF is halted. Freezing protection is assumed to be provided by the addition of glycol to the HTF. This

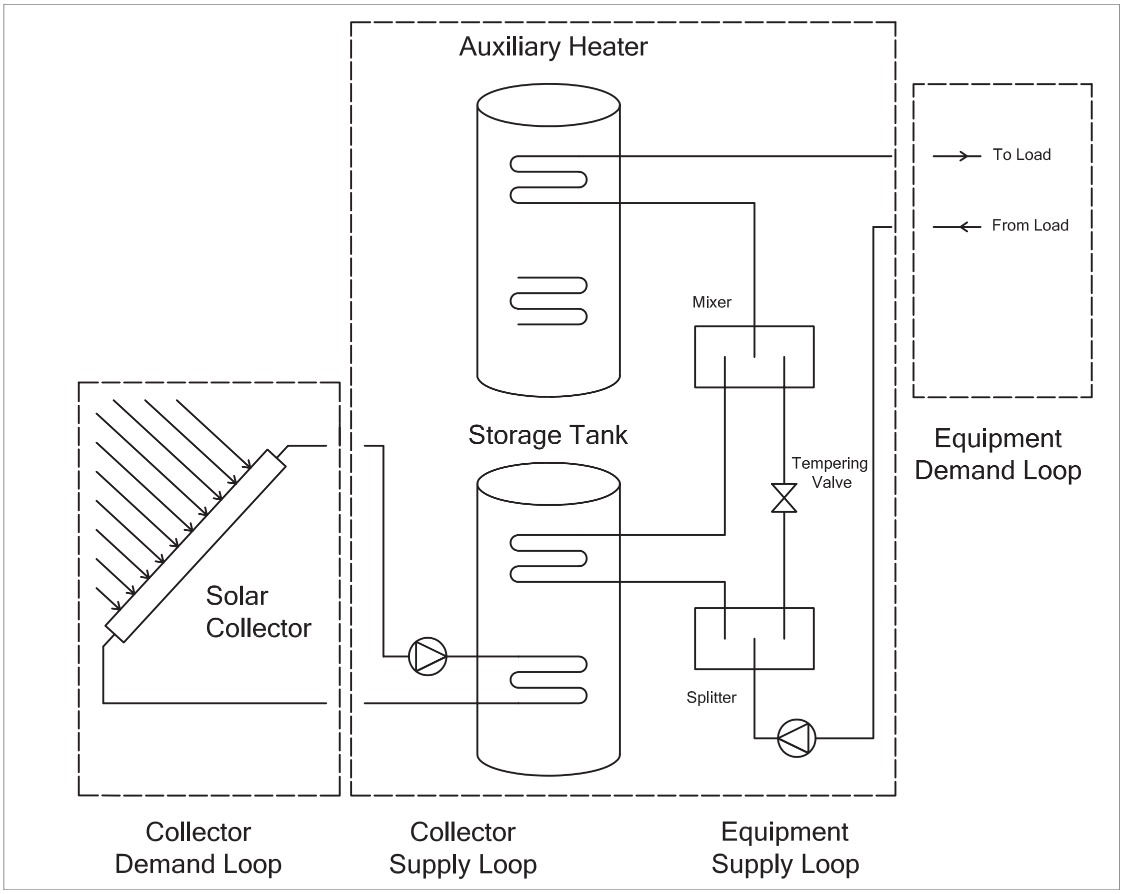

Figure 4.2: Diagram of solar thermal system used in EnergyPlus simulations (U.S. Department of Energy, 2010c, p.1376).

assumption introduces some error to the system simulations because EnergyPlus does not account for the difference in specific heat between glycol and water (U.S. Department of Energy, 2010b, p.1367). The entire collector array is simulated with all collectors plumbed in parallel.

4.2 Selection of a Weather File

EnergyPlus requires environmental data in the E/E file format to perform a simulation for a given location. Therefore, the first step to applying the algorithm for parametric EnergyPlus simulations described in Section 3.2.2.5 is to select a .epw weather file. This thesis uses a weather file selected based on the geographic location of the weather station relative to the case study site. There are four weather stations within 30 miles of the case study site that have E/E files available. These are Newark International Airport, Central Park in Manhattan, LaGuardia Airport in Queens, and John F. Kennedy Airport in Queens. The airport closest to the site and the .epw file selected for the simulations is Newark International Airport.

4.3 Obtaining Estimates of Space and Water Heating Loads

To run the EnergyPlus simulations with the shell script the school water and space heating loads must be estimated. Equation 3.1 requires four values to calculate the energy demand for heating hot water for a month: the mass of hot water required, the specific heat of the water, the temperature the hot water must be heated to, and the temperature of the water when it is delivered to the building. The specific heat and density of water are dependent on the temperature of the water. Values for these properties are readily available in tables (Duffie & Beckman, 2006, p. 856). The values of C_p and ρ are evaluated at the temperature of the mains water as determined by the correlation presented in Section 3.2.2.2 using the .epw weather file for the Newark Airport. Evaluating these properties at the mains water temperature gives the highest estimated load: 1.4% greater than evaluating at the minimum usable temperature, described in the next paragraph, and 0.7% greater than evaluating at the average of the two temperatures. These differences are small compared to the uncertainty in the load due to the estimates for occupancy; regardless, the highest estimate was selected to produce conservative results.

The minimum usable temperature was determined based on the guidelines in ASHRAE Handbook: Heating, Ventilating, and Air-Conditioning Applications, Chapter 49 Service Water Heating and on the typical supply temperatures for heat distribution systems. The temperature chosen for for this thesis is $T_{min} = 50$ °C. This temperature is the minimum temperature that is sufficient to meet the water and space heating demands. It is important to choose a temperature as low as possible because as the inlet temperature to the collector increases, a requirement to reach higher storage tank temperatures, the losses from the collector to the ambient increase, which decreases the collector efficiency. The value of T_{min} chosen is the lowest that is capable of meeting the requirements for both space heating and water heating. American Society of Heating, Refrigerating and Air-Conditioning

Table 4.1: Elementary School Domestic Hot Water Demand (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2007)

	Max Hour	Max Day	Average Day
ASHRAE Guidelines (gal/student)	0.6	1.5	0.6
Case Study Values (gal)	240	600	240

Engineers (2007) recommend a temperature of 40.5°C for hand washing and suggest that kitchens require temperatures in the range of $60 - 90.5$°C. The value of T_{min} selected is too low to meet the temperature required for the kitchen, but it is assumed that the difference between the two temperatures can be met through a high efficiency heating unit sized to meet the kitchen load based on a temperature difference from 50°C to the required temperature. The supply temperature to convector and radiator heat distribution systems are typically 50°C (Hegger et al., 2008, p. 126). The mass of hot water required is also based on the recommendations of American Society of Heating, Refrigerating and Air-Conditioning Engineers (2007) and the estimated occupancy of the school building. The school is expected to have 400 students. This number is used with the ASHRAE guidelines presented in Table 4.1 to develop estimates for daily required hot water. Multiplying the number of students by the values in Table 4.1 gives peak hourly, peak daily, and average daily hot water demands of 240 gallons/day, 600 gal/day, and 240 gallons/day respectively. The average values for schools account for holidays and weekends and are noted as suitable for estimating monthly average loads. The reduction in occupancy due to the summer vacation is accounted for by reducing the load by a fractional amount. The design team assumed that the reduction in occupancy during the summer would occur from the middle of June through the end of August. To account for this reduction the water heating load in June, July, and August was reduced by a factor of 0.6, 0.05, and 0.05 respectively. The temperature of the water entering the building is determined by the correlation of Equation 3.2, which is based on an analysis of temperatures available in the weather file. The results of developing the energy demand for water heating for the school are shown in Table 4.2 and in Figure 4.3. These results are presented as monthly total values to illustrate the annual trends in the demand. Hourly values were calculated and used as the inputs

Table 4.2: Elementary School Domestic Hot Water Demand in GJ (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2007)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Water	4.97	4.58	4.79	4.05	3.41	1.60	0.15	0.10	2.24	2.99	3.64	4.51
Space	98.02	79.71	70.71	48.65	4.49	0	0	0	0.09	13.19	63.31	83.33
Combined	102.99	84.29	75.50	52.70	7.91	1.60	0.15	0.10	2.34	16.19	66.95	87.84

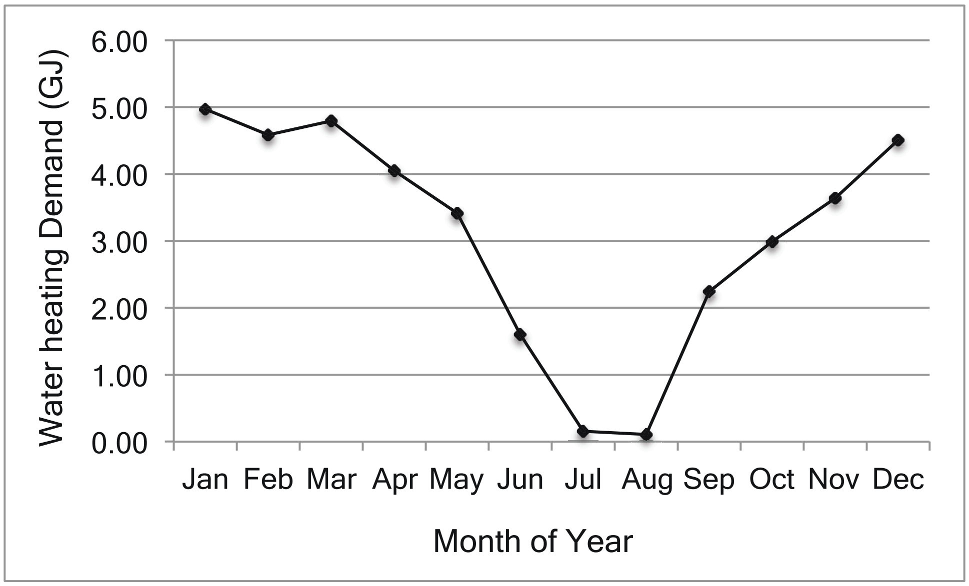

Figure 4.3: Water heating loads for school building.

to EnergyPlus.

The space heating load used to size the STS for this thesis was extracted from the results of a simulation of the performance of the proposed building. The simulation was performed using eQuest, a building energy simulation software based on the DOE-2 calculation engine, by the building engineering firm designing the school mechanical systems. The heating energy required each hour to maintain a comfortable indoor temperature is predicted by the eQuest program. The school modeled in the eQuest simulation is a two-story building with well-insulated concrete construction. The exterior walls and the roof are insulated by 3 inches and 6 inches of polyisocyanurate, respectively. The overall u-values for the walls and roof are calculated by the the method presented in Section 3.2.2.4 and are 0.24 W/m^2 °C (0.043 Btu/h ft^2 °F) and 0.16 W/m^2 °C (0.028 Btu/h ft^2 °F), respectively. The building model has a first floor area of 3,978 m^2 (42,816 ft^2) and a second floor area

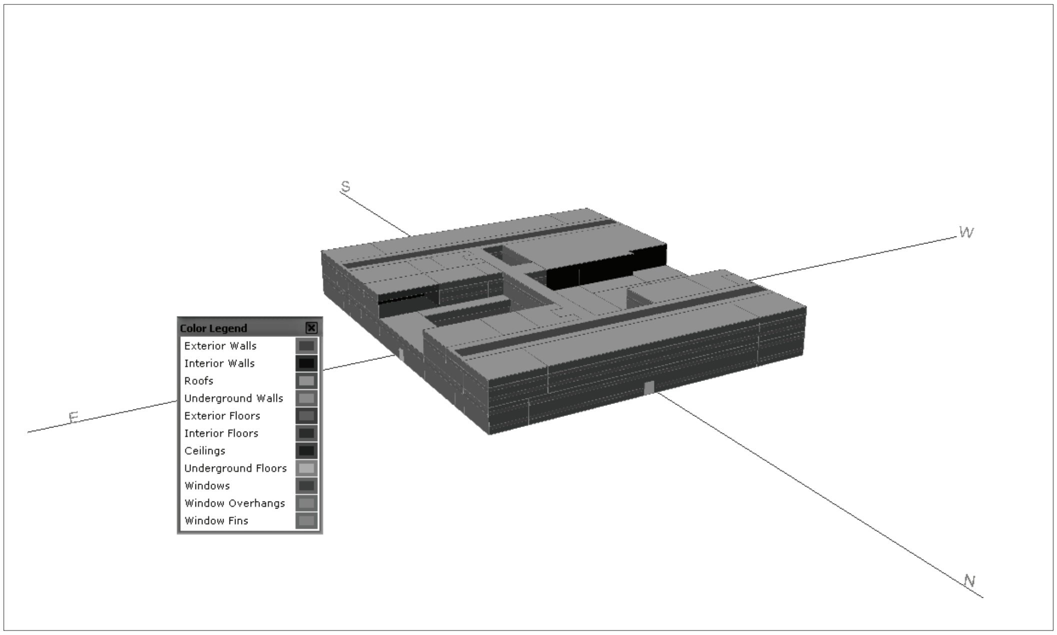

Figure 4.4: Screenshot of eQuest model edited by Ben Taylor. eQuest model prepared by Engineering firm.

of 2,437 m^2 (26,232 ft^2). The building form is compact as shown in Figure 4.4. The building heating set-points are 22.2 °C (72 °F) when the building is occupied and 17.8 °C (64 °F) when the building is unoccupied. The occupancy schedule follows a typically school day with occupancy beginning at 6 AM. Nearly full occupancy is assumed to be reached by 8 AM and sustained through 3 PM. From 3PM to 10 PM there is partially occupancy. For the hours from 10 PM through 5 AM the school is assumed to be unoccupied. Monthly totals for the school heating demand are shown in Table 4.2 and Figure 4.5.

The combined load was obtained by combining the water and space heating loads. The resulting combined load is shown in Table 4.2 and Figure 4.6.

The combined load from the water and space heating demands is in joules per hour. To use this load profile in EnergyPlus with the “LoadProfile:Plant” and “Schedule:File” objects it is necessary to convert the hourly demand for energy to hourly values for the plant mass flow rate and power demand. This was done by specifying an exit temperature and temperature difference across the inlet and outlet for the load loop drawing energy from the TS. The hourly load values in joules can then be divided by the loop temperature difference and the specific heat of water at

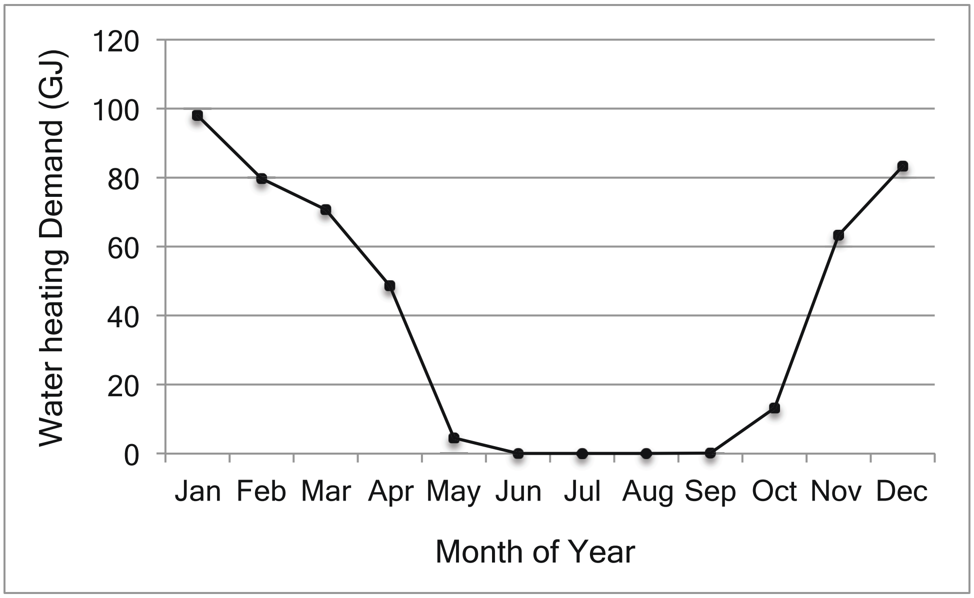

Figure 4.5: Space heating loads for school building.

the average loop temperature to determine a mass flow rate. The mass flow rate is divided by the density at the average loop temperature to convert to a volumetric flow rate. EnergyPlus requires that the mass flow rate be specified as a fractional schedule. To obtain a fractional schedule the hourly values for the volumetric flow rate are divided by the maximum volumetric flow rate for the year. This maximum value is specified in the .idf file and the fractional flow rate is imported to EnergyPlus with a “Schedule:File” object. The power demand for the plant is simply determined by dividing the hourly energy demand in joules by 3600 to obtain values in watts. These values are also imported to EnergyPlus with a “Schedule:File” object.

It is clear from Figures 4.3, 4.5, and 4.6 that the building demand for thermal energy is much greater during the winter season. This trend is nearly the inverse of the available solar resource as shown in Figure 4.7. Seasonal storage has the capability to overcome this mismatch between supply and demand by storing energy collected in the summer for use in the winter.

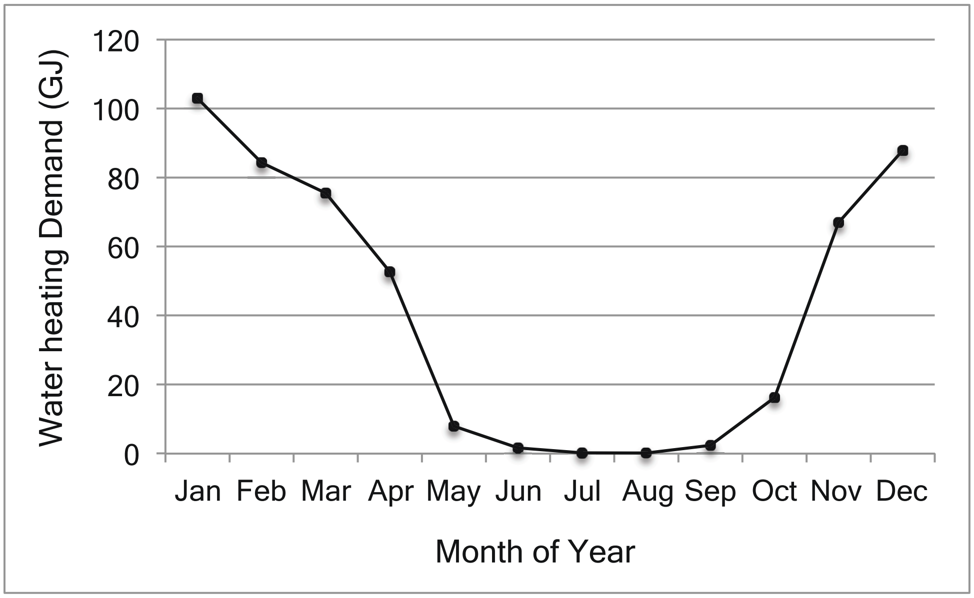

Figure 4.6: Total load used in EnergyPlus simulations.

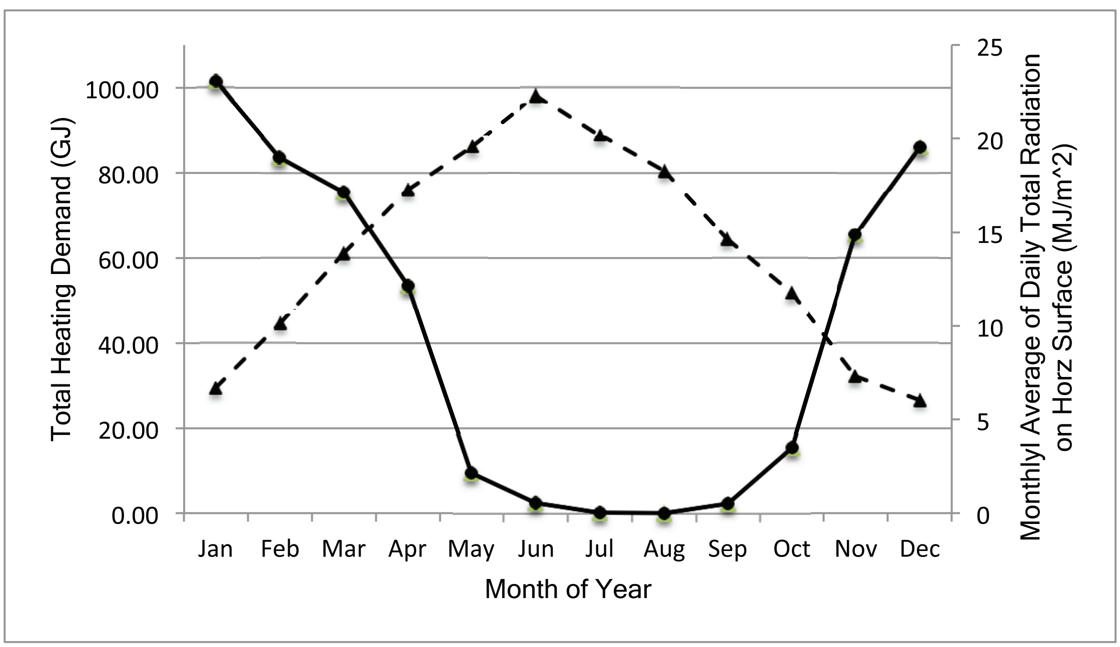

Figure 4.7: Total load used in EnergyPlus simulations and monthly average solar resource on a horizontal surface.

Table 4.3: Selected Collector Data from SRCC (Solar Rating and Certification Corporation, 2011b)

	Gross Area (m^2)	$F_R(\tau\alpha)$	$F_R(U_L)$	$K_{\tau\alpha}$
Ritter Energie CP6 XL INOX	1.15	0.555	-0.996	-0.12
Vaillant Solar Systems VFK 150 H	2.507	0.776	-3.464	-0.10

4.4 Selecting a Collector Based on Technical Performance and Aesthetic Requirements

Selection of a solar thermal collector for a building integrated STS can be made on a variety of criteria. These criteria range from the technical, $F_R(U_L)$ and $F_R(\tau\alpha)$ values, to the aesthetic. The cost of the collector and the cost to install the collector are also highly influential. Flat plate and evacuated tube collectors are the type of solar thermal collectors most often used to meet building energy demands due to their simplicity, low cost, and effectiveness within the temperature range typically required for building applications. For these reasons and due to the applicability of the collector model presented in Section 3.2.2.3 these two types of collectors will be compared based on their performance and aesthetics and a collector representative of the chosen type will be selected from the SRCC database to used in the EnergyPlus simulations. Simulations are performed using a collector representative of the type not originally selected for a limited number of storage volume to collector area ratios. These simulations are used for final evaluation of the effectiveness of the flat plate versus the evacuated tube collectors based on annual SF's.

Figure 4.8 is a plot of the $F_R(\tau\alpha)$ versus the $F_R(U_L)$ values for all of the evacuated tube and flat plate collectors in the SRCC OG-100 directory of collector ratings. The clustering of the points for the two types of collectors clearly shows that flat plate collectors typically have higher heat gain coefficients, $F_R(\tau\alpha)$, while the evacuated tubes have lower heat loss coefficients, $F_R(U_L)$. The circles denote collectors which have optimal values for $F_R(\tau\alpha)$ and $F_R(U_L)$ for their collector type. The manufacturer, model, gross area, $F_R(\tau\alpha)$, $F_R(U_L)$, and $K_{\tau\alpha}$ for the selected collectors are provided in Table 4.3.

Flat plate collectors and evacuated tube collectors have distinctive appearances. Flat plate collectors are more similar to traditional building materials and

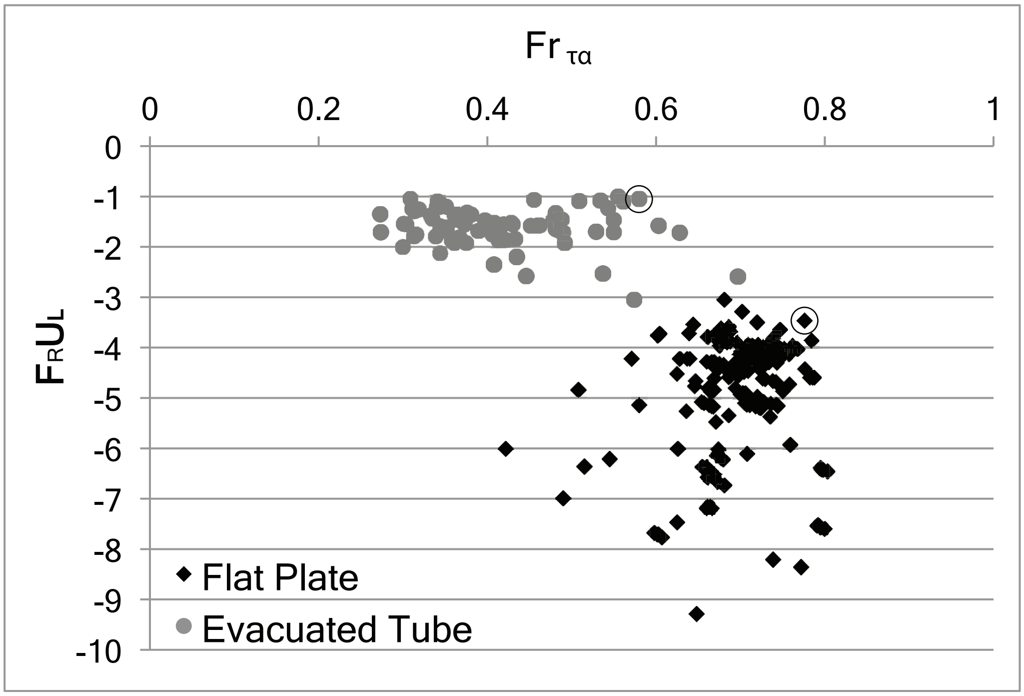

Figure 4.8: SRCC collector performance parameters for evacuated tube and flat plate collectors (Solar Rating and Certification Corporation, 2011b).

resemble large skylights because of the single flat glazing. Evacuated tubes are composed of tubes of glass that feed into a manifold and are less visually uniform as a result. Figure 4.9 illustrates the visual differences between the two collector types with a typical photovoltaic panel for reference and without the context of a building.

The continuity of the glazing of a flat plate collector makes it possible to replace the outer layer of the building roof or wall with the collector itself. This can provide for better integration with the architecture of the building when compared to mounting the solar collectors above a traditional roofing material. Additionally, this can potentially reduce the material cost for the building, which helps to offset the additional cost of the STS. The case studies presented in Section 2.4 provide examples of solar thermal collectors that are the external roofing surface and solar thermal collectors that are mounted above the roofing surface. Images of these systems are shown for comparison in Figure 4.10. The school building is expected to have a large array of PV solar collectors in addition to the solar thermal collectors.

Figure 4.9: Evacuated tube thermal collector (TradeSohu Inc, 2011), flat plate collector (Solar Panels Plus, 2011), and photovoltaic electric collector (Solar Conduit, 2011).

Figure 4.10: Additive (Young, 2010) and integrated flat plate collectors (Jenni Energietechnik, 2011b).

For this reason, it is important to consider the appearance of the PV and the solar thermal collectors comparatively. Figure 4.9 shows a PV module on the far right next to two solar thermal collectors, the evacuated tube on the left and a flat plate in the center. This comparison suggests that the flat plate collector is more similar to the PV collector. If the goal is to maintain a consistent appearance across a building surface that has PV panels installed, then flat plate collectors are a better option compared to the evacuated tube collectors.

Due to the potential for lower system costs, better visual continuity and adequate performance the Vaillant Solar Systems VFK 150 H flat plate collector from Table 4.3 was chosen for use in the EnergyPlus simulations. The flat plate collector is expected to perform better than the evacuated tube collector in the summer, when there is a lower temperature difference between the collector and surroundings. This increase in summer performance should have a greater effect on the annual performance of the system, measured by the SF, than the potential increase in performance in the winter due to the superior thermal insulation of the evacuated tubes. The performance of the collectors will be simulated for an ideal physical orientation. From the discussion in Section 2.3.1 the ideal orientation for annual energy gain is due south with a slope equal to the latitude. The EnergyPlus simulations will be performed with the collectors facing due south and with a tilt of 40 degrees from horizontal, which is approximately equal to the latitude of Staten Island.

4.5 Estimating the Thermal Storage Overall Heat Loss Coefficients

The EnergyPlus water storage tank object requires an input for the value of the overall heat loss coefficient and the effectiveness of the heat exchangers between the tank and the collectors and the tank and the load. EnergyPlus uses the overall heat loss coefficient to calculate the heat loss from the storage tank based on Equation 3.10. This section describes the heat exchanger effectiveness value and the various thermal storage materials, containers, and insulating materials used to calculate $(UA)_s$ values for the range of storage tank volumes in the parametric EnergyPlus simulations.

To determine a value for the heat loss coefficient for a steel tank the overall heat transfer coefficient from the water within the tank through the wall and insulation to the surroundings must be calculated. The surface area of the outer layer of the tank must also be calculated. If the tank is insulated, the surface area of the insulation must be calculated. Figure 4.11 shows the components of a steel thermal storage tank that are relevant to the calculation of a one-dimensional U-value. The calculations performed in this thesis are based on a stainless steel cylindrical tank with a wall thickness of 7 mm and a thermal conductivity of 16 W/mK (The

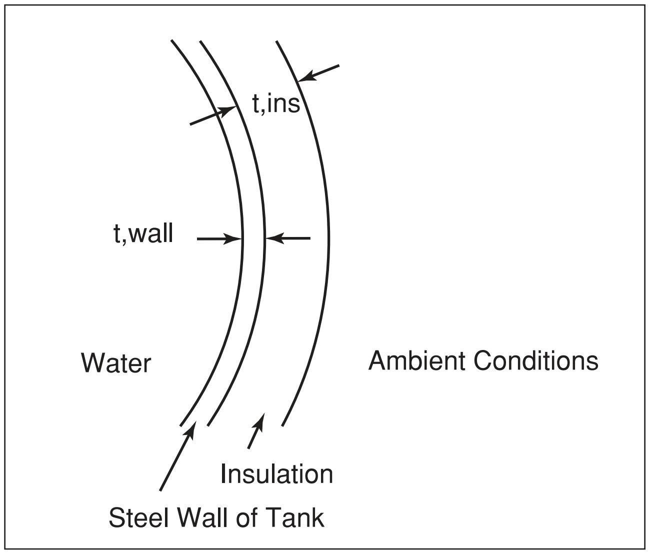

Figure 4.11: Components of a water thermal storage tank relevant to the calculation of U-values.

Engineering Toolbox, 2011). The tank is assumed to be within the building envelope and the tank surroundings are maintained at a room temperature of 22°C throughout the year. In this situation thermal losses from the tank are gains to the surrounding building. This effect is not accounted for and could cause the results to be slightly conservative. The insulation is a polyurethane insulation with a thermal conductivity of 0.02 W/mK (The Engineering Toolbox, 2011). The optimal insulation thickness depends on the volume and proportions of the thermal storage. A height to diameter ratio of 1:3 was selected to provide a tank with proportions that facilitate thermal stratification as described in Section 3.1.2.3. To determine the effect of the insulation thickness on the overall heat loss coefficient UA values were calculated for a range of insulation thicknesses and storage volumes using Equation 3.13. The value for the convective heat transfer coefficient, h, was calculated to be 4.39 W/m^{2}K. The results of these calculations are shown in Figure 4.12, which clearly shows that the overall heat transfer coefficient, UA, decreases dramatically as the insulation thickness begins to increase. After the insulation thickness increases to a certain point the rate of change of the UA value begins to decrease rapidly. The trend for different size storage volumes is the same, but the larger storage volumes require significantly thicker insulation to achieve the same rate of

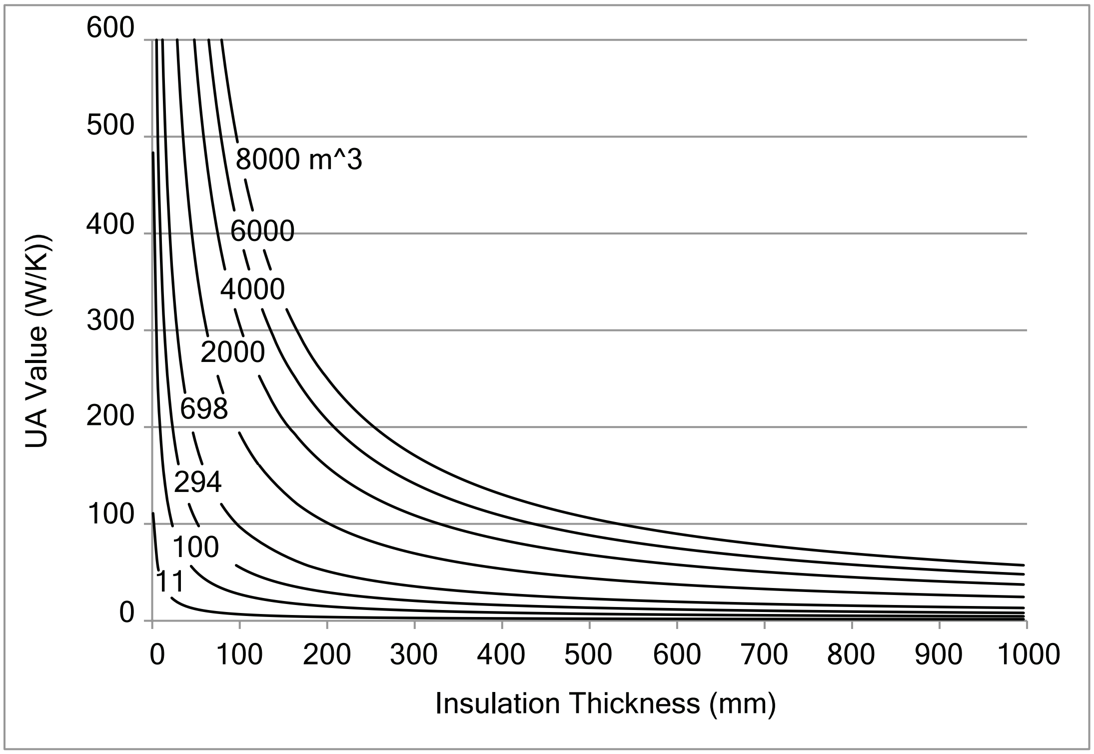

Figure 4.12: Effect of insulation thickness on overall heat loss coefficients for a range of storage volumes. Values are for cylindrical volumes with a height to diameter ratio of 3.

decrease in the UA value. To obtain comparable parametric simulation results it was necessary to obtain a function relating the storage volume to the insulation thickness that could be used to calculate insulation thicknesses that would generate proportionally similar UA values for varying storage volumes. To obtain this function exponential functions were fitted to the curves in Figure 4.12. A slope of -0.15 was selected as the point where further increasing the insulation thickness would not have a significant effect on the UA value and therefore on the heat lost from the storage. The insulation thickness where the rate of decrease in the UA value is -0.15 was calculated for the storage volumes in Figure 4.12. These insulation thicknesses were then plotted against the storage volumes as shown in Figure 4.13. A curve was fitted to the points in this graph, which was then used to calculate insulation thicknesses for the different storage volumes of the parametric simulations. The insulation thicknesses calculated with this function were used in the calculation of UA values for the parametric simulations.

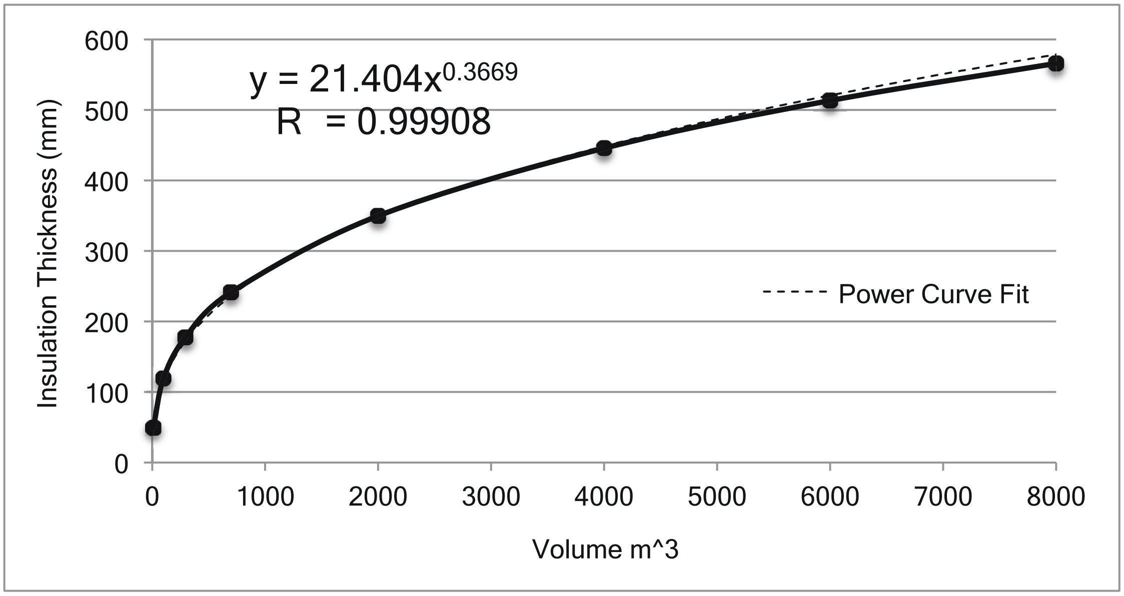

Figure 4.13: Tank versus insulation thickness for -0.15 rate of decrease in the UA value.

This section described the assumptions made and the notable input values selected for implementation of EnergyPlus as a simulation tool to obtain the range of collector area and storage volume combinations appropriately sized to the water and space heating demands of a net-zero energy school in the New York City borough of Staten Island. These inputs and assumptions were used with the shell script described in Section 3.2.2.5 to obtain results that are presented in Section 5. Table 4.4 provides a summary of the parameters and assumptions used in the EnergyPlus simulations run by the shell script.

Table 4.4: Summary of System Parameters and Assumptions

Collector		
Manufacturer	Vaillant Solar Systems	
Model No.	VFK 150H	
Gross Area	2.507	m^2
Fluid	water	
Test Flow Rate	0.0000526	m^3/sec
Eff Eq. Coeff 1 ($F_r(\tau\alpha)$)	0.776	
Eff Eq. Coeff 2 ($F_r U_L$)	-3.464	
Inc. Angle Modifier Coeff 2 (b_o)	-0.10	
Tilt	40	
Azimuth	South	
Space and Water Heating Demands		
Water Thermal Prop. Eval. Temp.	Mains Water Temp.	
Minimum Usable Temp.	50	°C
Hot Water Demand	240	gal/day
Demand Loop Setpoint Temp.	60	°C
Demand Loop Design Temp. Drop	10	°C
Weather File	Newark Intl. Airport .epw	
Storage Tank		
Stratification	Fully Mixed	
Surroundings Temp	22	°C
Wall Thickness	7	mm
Wall Material	Steel	
Wall Thermal Conductivity	16	W/mK
Insulation Material	Polyurethane Foam	
Insulation Thermal Conductivity	0.02	W/mK
Height to Diameter Ratio	3	
Maximum Temperature	98	°C
Balance of System		
Collector Loop Flow Rate	variable	
Collector Loop On Differential	10	°C
Collector Loop Off Differential	2	°C
High Temp. Off Set Point	98	°C
Low Temp. On Set Point	none	
Array Plumbing	parallel	
System Type	closed loop, pressurized glycol, with tempering valve	
Shell Input Command		
ePlusDesSpaceFunc.sh newark.epw 138.49 21 0.001 10		

5. Results: Collector Area and Storage Volume Combinations Appropriate to the Net-Zero Energy School

The assumptions and parameter values presented in Chapter 4 were used in the application of the shell script and EnergyPlus calculation engine described in Section 3.2.2.5 to determine a range of collector area and storage volume combinations appropriate to the water and space heating load of a ZEB elementary school in Staten Island. The results of these simulations are presented in this section.

The effect of the collector area on the annual SF is presented in Figure 5.1 for diurnal and seasonal scale storage. It is clear that for smaller storage volumes increasing the collector area will cause a gradual increase in the annual SF. For seasonal scale TS, the annual SF increases at a greater rate and reaches annual SFs that are not obtained by the system with diurnal scale TS.

The complete results of the parametric EnergyPlus simulations run by the shell script program described in Section 3.2.2.5 are shown in Figure 5.2. As expected these results follow the trends identified by Braun et al. (1980). The results presented

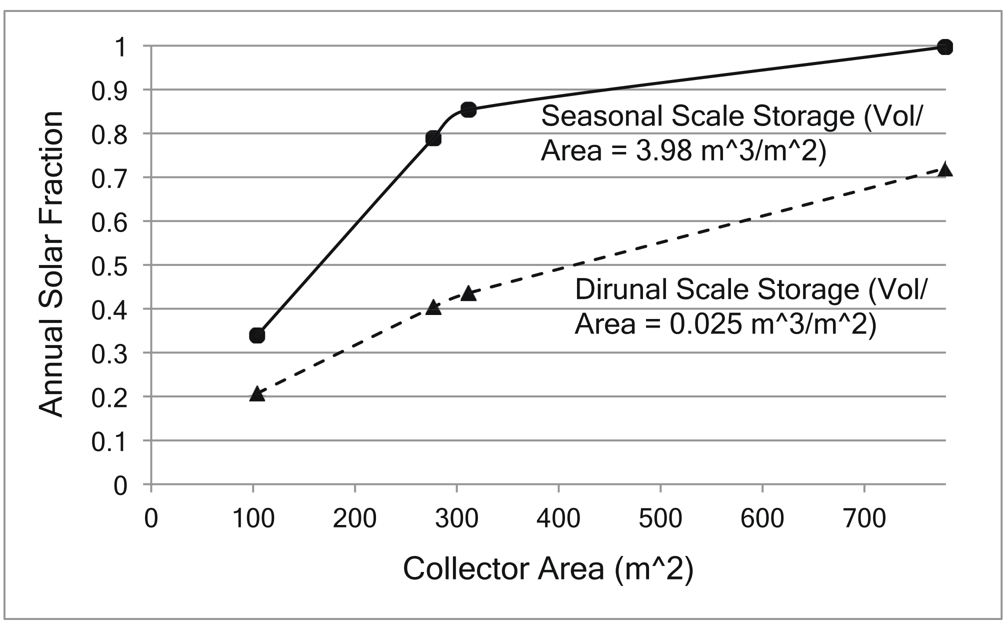

Figure 5.1: Effect of collector area on the annual solar fraction for varying seasonal and diurnal scale thermal storage.

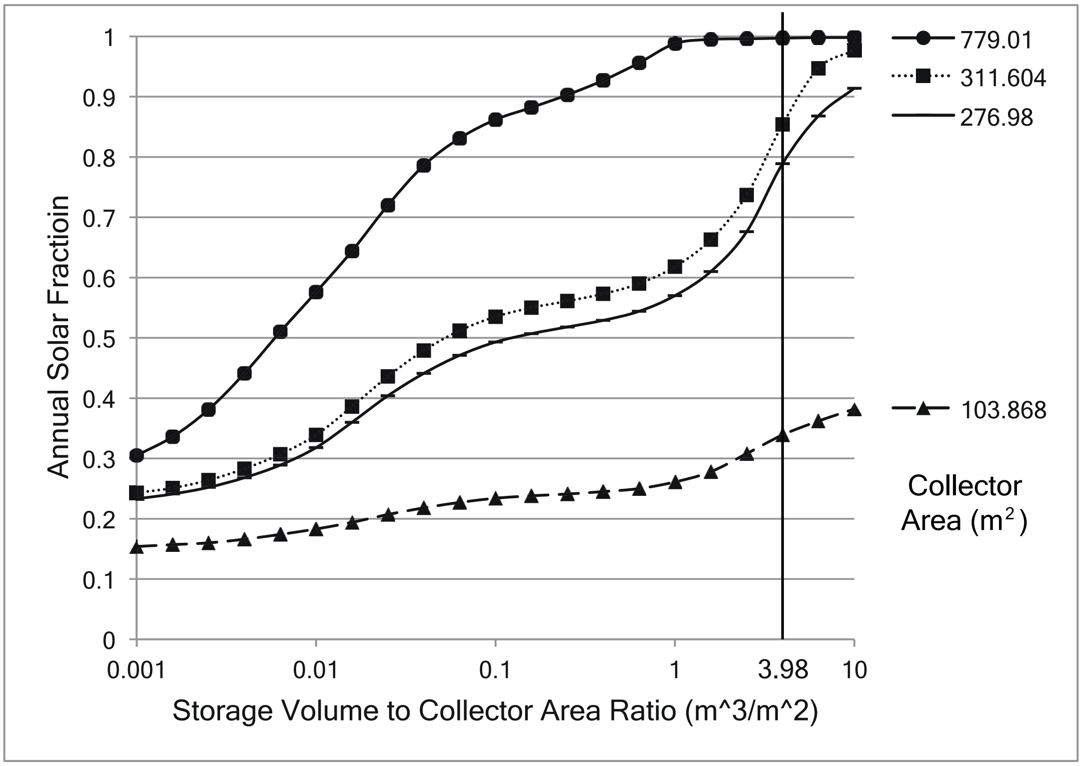

Figure 5.2: Effect of storage volume on the annual solar fraction for four different size collector arrays.

in Figure 5.2 cover a wide range of possible combinations of collector areas and TS capacities providing SFs from 15% to 100%. Each curve in Figure 5.2 shows the effect of varying TS capacity for a system with a constant collector area and has two regions with little change and two regions with rapid change. The regions with little change indicate where the performance of the STS is relatively independent of the volume of TS. The flatter areas adjacent to the ordinate denote TS volumes that do not have enough capacity to overcome diurnal mismatches between the available solar energy and the demand for thermal energy, while the second flat region denotes TS volumes that have more than enough storage capacity for diurnal mismatches between supply and demand but not enough to overcome seasonal mismatches. The two middle curves for systems with collector areas of 311.60 m^2 and 277 m^2 show how seasonal scale TS can greatly increase the annual SF from values around 50% to 100%. The points in Figure 5.2 for a storage volume to collector area ratio of 3.98 m^3/m^2, marked by the solid vertical line, are presented in Figure 5.3. The

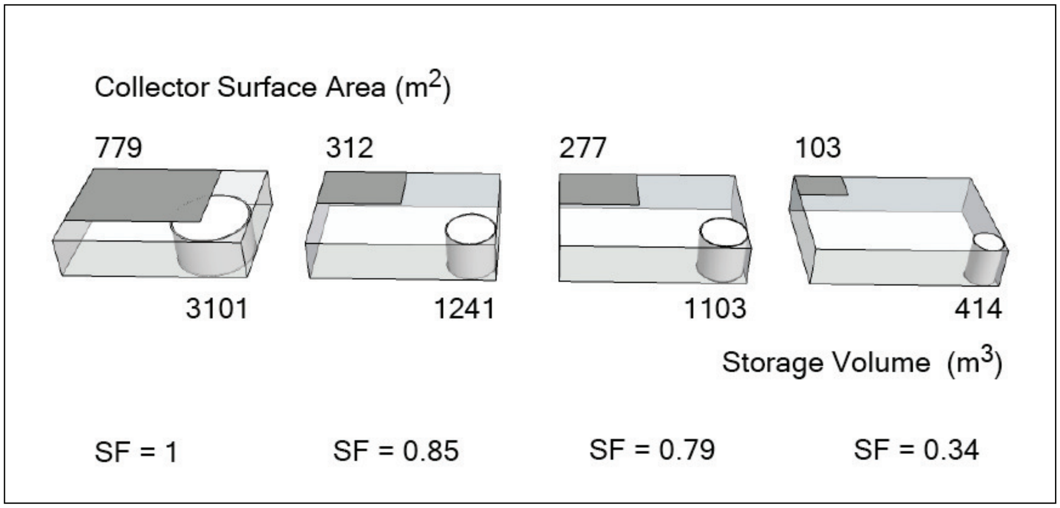

Figure 5.3: Visual comparison of the collector area and storage volume combinations compared to building volume.

data for the storage volume to collector area ratio of 3.98 m^3/m^2 are shown visually because this is the first seasonal storage volume to collector ratio that provides a SF above 80% due to the effects of seasonal storage rather than collector area. SFs of 80% are the upper limit for STSs with diurnal scale TS as noted in Chapter 1. Figure 5.3 provides a more qualitative understanding of the scale of the collector areas and storage volumes presented in Figure 5.2. The rectangular volumes in Figure 5.3 represent the volume of a three-story building with 3.66 m (12 ft) floor heights and a roof area equal to the area of the PV array in Figure 4.1, 1430 m^2 (15,392 ft^2). The grey rectangular areas provide a comparison of the collector area versus the roof area available for the PV array and the cylindrical volumes provide a comparison of the volume of the storage tank versus the volume of the building, if the height of the storage tank is constrained to the height of the building. These visual comparisons suggest that the collector area needed to provide high solar fractions could potentially be placed entirely on the roof. This is a positive result because, as described in Section 2.3, Torcellini et al. (2006) rank renewable energy generated within the building footprint higher than renewable energy generated on-site but outside the footprint of the building. The comparison of the thermal storage volume to the building volume in Figure 5.3 suggests that to achieve large solar fractions through seasonal scale thermal storage the storage volume must approach the scale

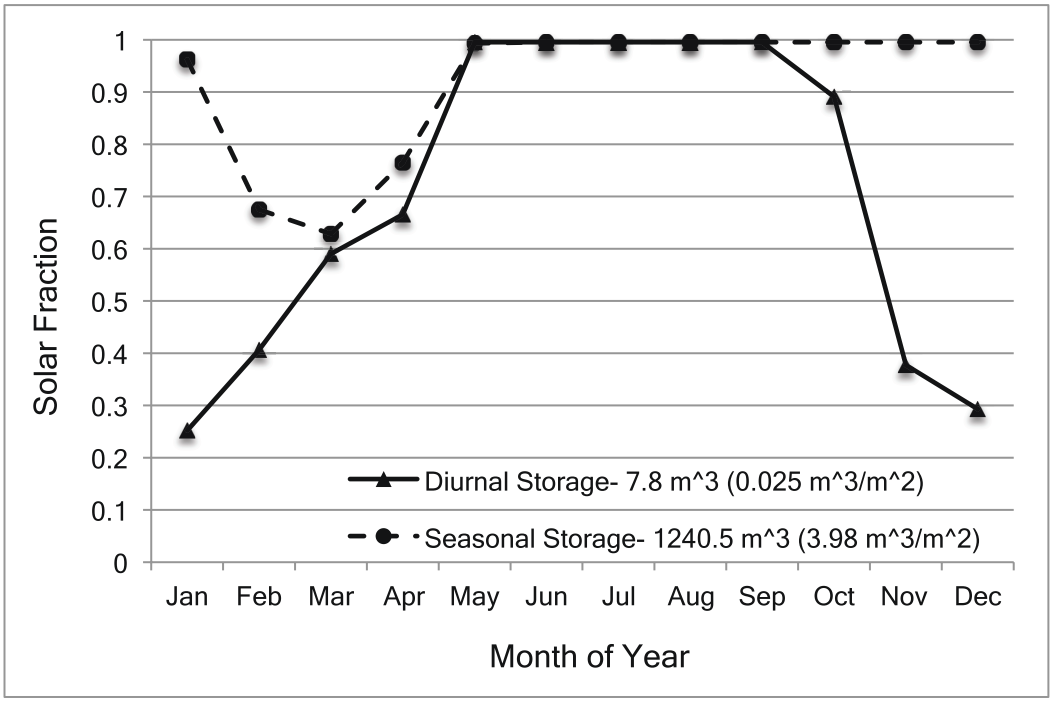

Figure 5.4: Monthly solar fraction for diurnal and seasonal scale thermal storage with a 311.6 m^2 collector array.

of the building itself. This scale of thermal storage is unlikely to be economically or architecturally feasible if implemented in the form of an insulated steel tank. Other strategies for achieving seasonal scale storage, as described in Section 3.1.2.2, may be more viable for the case study and will be discussed in Section 6.

The monthly SFs for systems with a collector area of 311.6 m^2 and storage volume to collector area ratios of 0.025 and 3.98 are plotted in Figure 5.4. The difference between the performance of a STS with seasonal scale and diurnal scale TS are clear. The system with diurnal scale TS provides all the space and water heating demand in the summer when the demand is low and the solar resource is abundant, but provides only a small fraction of the demand when the solar resource is low and the demand is high. This is in contrast to the performance of the system with seasonal scale storage, which meets the loads throughout the year except in the late winter season when the thermal storage capacity has been depleted and the demand for heating is still high relative to the availability of the solar resource.

Table 5.1: Annual Solar Fraction for all E/E Weather Files Within 30 Miles of Site

	Newark Airport	Central Park	LaGuardia Airport	JFK Airport
Solar Fraction	0.854	0.861	0.871	0.854

5.1 Sensitivity Analyses

The primary design parameters, those with the greatest influence on the SF, are the collector area and the storage volume if the other system parameters are close to commonly accepted values (Duffie & Beckman, 2006). The effects of varying these two parameters were analyzed thoroughly to produce the results presented in the beginning of this chapter. To confirm the relative lack of influence of other parameters sensitivity analyses were performed on the effects of the weather file and the type of collector chosen.

5.1.1 Sensitivity of Simulations to the Selected Weather File

The simulation of the STS's with collector area and storage volume of 311.6 m^2 and 1240.5 m^3 respectively was selected for simulation with the weather files for the locations within 30 miles of the case study site as described in Section 4.2. This combination of collector area and storage volume is the most sensitive as illustrated by the relatively large distance between the surrounding points on the constant collector area line in Figure 5.2. The results of the simulation of this system configuration with the weather files for Newark International Airport, Central Park in Manhattan, LaGuardia Airport in Queens, and John F. Kennedy Airport in Queens are presented in Table 5.1. Simulating the STS with the weather file for LaGuardia Airport results in the greatest difference, an annual SF that is 0.017 higher than the result for the Newark Airport. This difference is minimal and the original selection of Newark for the simulations is valid.

5.1.2 Sensitivity of the Simulations to the Collector Parameters

The collector area and storage volume simulation selected for analysis of the sensitivity of the simulations to the selection of a weather file was also simulated with collector parameters representative of an evacuated tube collector. The evacuated tube collector selected was the Ritter Energie CP6 XL INOX, as described in Section

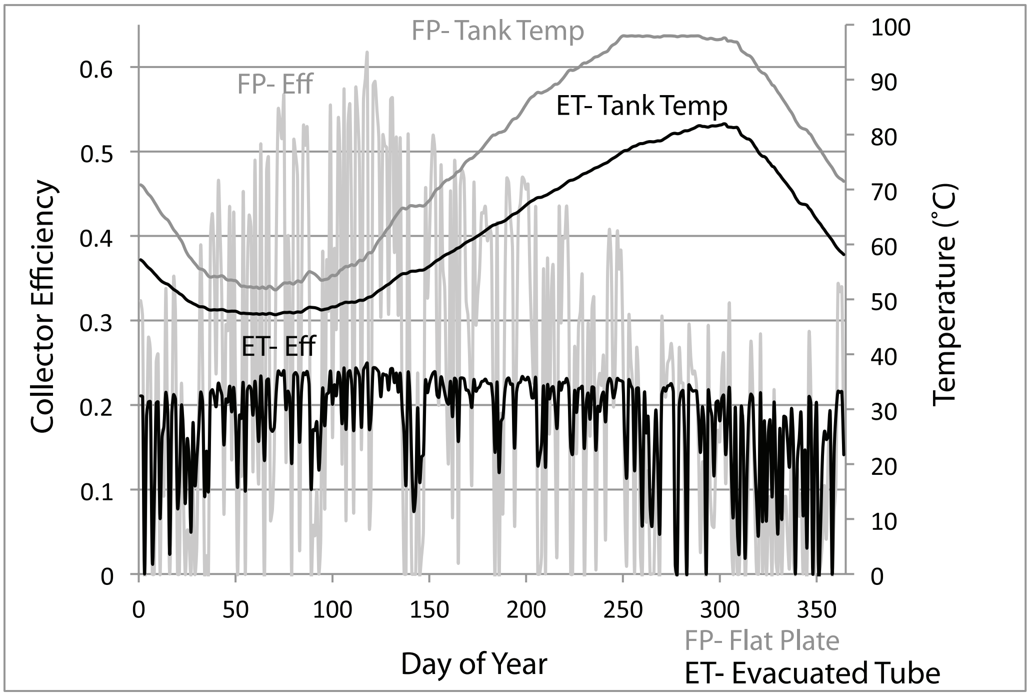

Figure 5.5: Collector efficiency and storage tank temperature for a system with flat plate collectors and a system with evacuated tube collectors.

4.4. The "Shading:Site:Detailed" and the "SolarCollectorPerformance:FlatPlate" objects were modified to reflect the parameters of the evacuated tube collector as shown in Table 4.3. The results of the simulations comparing the performance of the flat plate and evacuated tube collector are presented in Figure 5.5. The daily average efficiency for the period of the day with the most solar gains (9AM to 3PM) for each type of collector are plotted in addition to the average daily temperature of the storage tank. Although the evacuated tube collector operates more consistently, the flat plate collector operates at a much higher efficiency during the majority of the year. The advantage of the low heat loss coefficient of the evacuated tube is observed toward the end of the year when the storage tank temperature is elevated and the ambient temperature is low. During this period the evacuated tube collector operates with a higher efficiency than the flat plate collector. Ultimately, the system simulated with the flat plate collector provides an annual SF of 0.854, while the system simulated with the evacuated tube collector results in an annual SF of 0.654. These results validate the selection of the flat plate collector based on technical criteria for the conditions of the case study. In this case the technical criteria support the architectural criteria that the appearance of the STS collector closely match the appearance of the PV modules.

5.2 Implications of Results

The results indicate that the type and scale of the solar thermal collectors necessary to provide large fractions of the space and water heating demand for ZEB school in Staten Island are feasible with regards to architectural aesthetics and area requirements. The scale of thermal storage required to achieve high SFs is more challenging. The space required to implement seasonal scale thermal storage using water contained in an insulated steel tank is too great to integrate with the architecture of the building. The largest solar thermal collector area obtained from the shell script, 779 m^2, takes up over half of the roof area available for energy systems, PV or ST. If roof area used by the PV system is made available to the solar thermal system it would be possible to obtain higher SF's by further increasing the solar thermal collection area. However, this strategy will produce diminishing results as the collection area is increased without adding storage capacity. Additionally, the collector is typically the most expensive portion of the solar system (Cooper, 2008), so it is financially beneficial to maximize the SF with a minimum collector area. Strategies for implementing seasonal scale thermal storage with different storage mediums or containers are explored in Section 6.

6. Future Work: Low Temperature Seasonal Storage with Passive Energy Delivery

This section discusses utilizing the building foundation of the case study as the seasonal thermal storage system. Design of such a thermal storage system will be the focus of future research. Preliminary calculations are presented to support the feasibility of this type of seasonal storage. Additionally, this section presents relevant design issues, potential benefits, and expected technical challenges.

Four design issues are important to all types of thermal storage systems: the storage medium, the charging method, the discharging method, and minimizing stand-by losses. The future work proposed reduces the additional storage volume of STS's with seasonal scale storage by addressing these design issues. Utilizing the foundation as the storage medium eliminates the need for a large insulated volume that is additional to the components of a typical building. Additionally, the goal of the future work is to realize the transfer of thermal energy directly from the TS to the building through the slab. Control of this heat transfer is potentially possible through an analog system designed around the properties of the materials separating the building slab from the TS. This would eliminate the need for an additional building system to distribute heat from the TS to the building.

The most common materials used for thermal storage are presented in Section 3.1.2. The sensible storage materials discussed are water, rock, soil, and concrete. Section 2.4 describes the use of the concrete floor of a residential building for thermal storage. Section 3.1.2 includes references to large seasonal storage systems that have successfully utilized gravel-water and borehole storage methods. A method of reducing stand-by losses by burying the thermal storage is described by Pinel et al. (2011) in Section 3.1.2.4. The thermal storage system discussed here draws from these methods to achieve seasonal scale thermal storage with the building foundation.

Figure 6.1 shows a conceptual diagram of the heat loss from a thermal store located beneath a building. Simplified calculations of the heat loss were made to

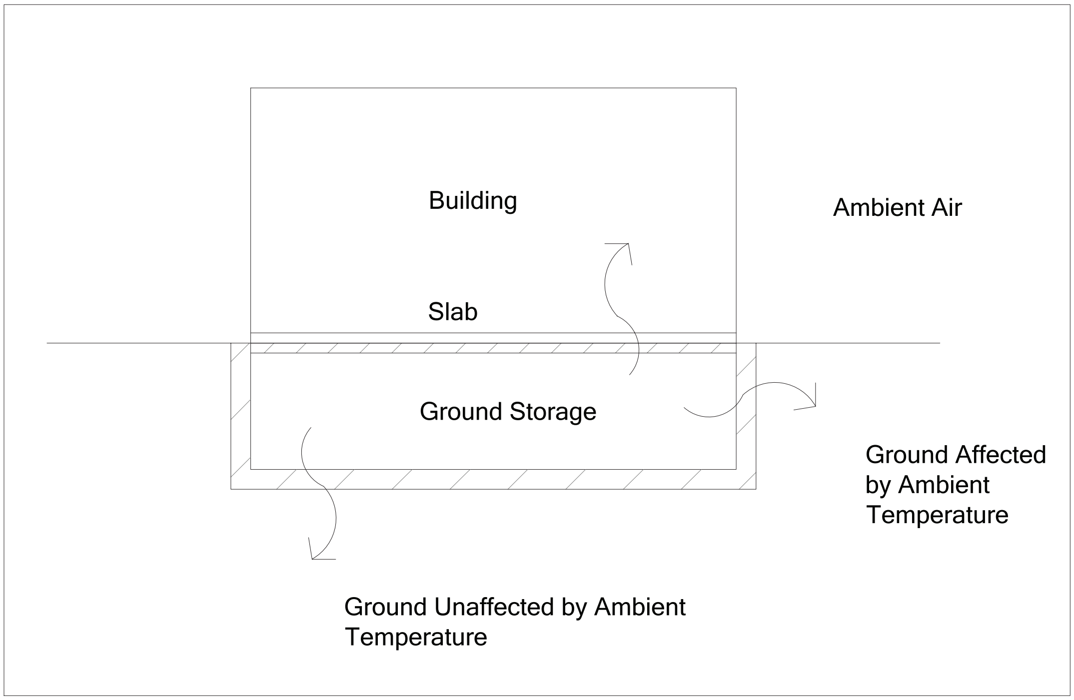

Figure 6.1: Conceptual diagram of approximate heat loss from a thermal storage system located beneath a building.

assess the feasibility of this type of storage system. The heat loss from the store was broken into three different conduction paths based on the geometry of the thermal store and the different surroundings. The top of the store is assumed to lose heat through a layer of insulation and a concrete slab into the building, which is assumed to have a constant temperature. The sides of the store are assumed to lose heat to the ground, which is assumed to have a fluctuating temperature based on the mean of the mean ambient temperature and the constant ground temperature, assumed to be the annual mean temperature. The bottom of the store is assumed to lose heat to the ground, which is assumed to be at a constant temperature. The heat losses are calculated using Equation 3.10. The storage capacity and dimensions of the thermal storage is based on the simulated system with 311.604 m^2 of collector area and 1240 m^3 of storage volume.

Calculating the thermal storage capacity for this system using Equation 3.11 over an annual temperature change from 47°C to 93 °C gives a capacity of 240 GJ. Table 6.1 provides the depths necessary to achieve this storage capacity for

Table 6.1: Storage Depth to Achieve 240 GJ Capacity and Annual Thermal Losses for Slab Thermal Storage with a Cross Sectional Area of 1430 m^2.

	47-93°C	22-31°C
Depth for Concrete	2.11 m (6.94 ft)	10.8 m (35.5 ft)
Depth for Rock	1.8m (6 ft)	9.4m (30.7 ft)
Losses	31.7 GJ	5.7 GJ

two different materials, rock and concrete, and two different operating temperature ranges. The density and specific heat of rock is 2500 kg/m^3 and 0.80 kJ/kg°C, respectively; the density and specific heat of concrete is 1922.2 kg/m^3 and 0.90 kJ/kg°C, respectively. In addition to the depths Table 6.1 contains an estimate of the annual thermal losses for each operating temperature range, if the storage insulation is 0.29m thick.

These preliminary calculations suggest that it is feasible to construct a thermal storage system of seasonal scale for the water and space heating demands of a school building in the Staten Island Borough of NYC. A gravel water storage system is potentially a better design than one relying solely on concrete as the thermal storage medium due to the smaller volume required.

These calculations show that a reduction in the operating temperature range of the thermal storage can reduce the stand-by losses despite the increase in surface area. If the operating temperature range is near the temperature that is required within the building there is the potential for heating the building directly by conduction from the storage into the building. Peak storage temperatures for seasonal storage are in the late summer and early fall, which is not a season that requires significant space heating. This is a potential difficulty with the direct release of heat into the building from the thermal storage system. A passive regulating system that utilizes materials which respond to fluctuations in temperature with changes in their shape, could provide a mechanically simple means for regulating the flow of energy from the thermal store to the building. A PCM could potentially provide this functionality. An advantage of PCMs is their ability to store large quantities of heat over small temperature ranges. Two properties often described as disadvantages of PCM's are their high thermal expansion coefficients and their low thermal

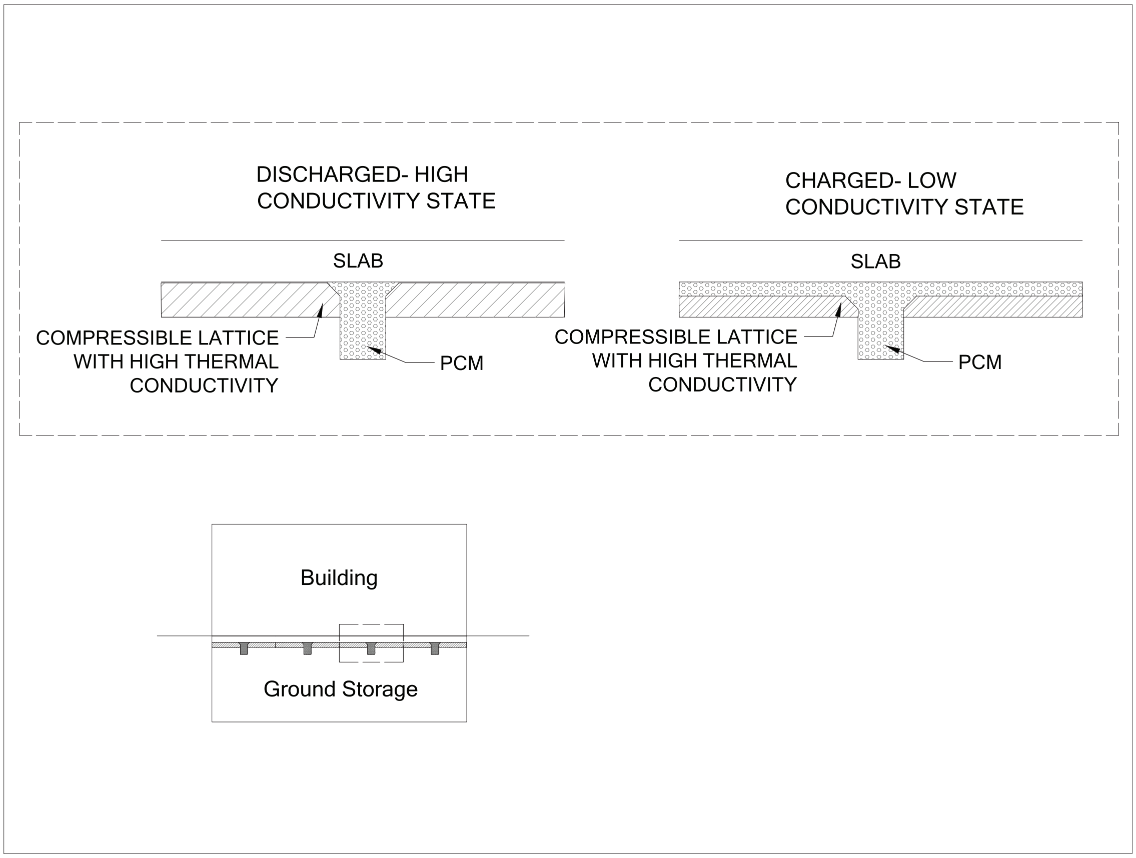

Figure 6.2: Conceptual diagram of approximate heat loss from a thermal storage system located beneath a building.

conductivity. These two features are potentially useful in this application. The thermal expansion could be used to spread the PCM across the boundary between the building and the thermal store when the thermal store is at high temperature. Because the thermal storage typically reaches its peak temperature before the demand for thermal energy peaks, as shown in Figure 5.5, this action could be used to store energy and reduce conduction of heat from the thermal storage to the building. Figure 6.2 shows a possible design for a foundation seasonal scale storage interface with a building slab that would regulate thermal conduction via fluctuating material distributions while increasing the storage capacity of the thermal storage. Cycling of the PCM component of the thermal storage is expected to be a crucial design issue. A driving force that insures the PCM returns to the correct physical location when solidifying will likely be necessary. A means for transferring heat from the solar array to the gravel-water storage is also an important design issue. This is typically done using water or air. Water would be preferable due to its higher heat capacity, but may be undesirable due to the function of the thermal store as a member of the building foundation. The delivery of heat from the solar array to the thermal storage system must be carefully considered to ensure compatibility with the remainder of the thermal storage system.

Future research will investigate designs for thermal storage that have seasonal thermal capacities over low temperature ranges and are capable of self-regulating the release of energy to the building for space heating. A thermal storage system with this capability could increase the adoption of seasonal scale thermal storage and thus increase the prevalence of STS's that provide SF's in the range of 80-90%.

7. Conclusions

This thesis presented a parametric study of building integrated solar systems that are capable of offsetting a large portion of a building energy demand with solar generated energy, specifically within the context of a Net-Zero Energy (NZE) school in the Staten Island Borough of New York City.

A Unix Bash shell script was used to run EnergyPlus simulations. The results of these simulations demonstrated the technical feasibility of designing a solar thermal system with seasonal storage to offset large portions of the water and space heating demand for a school in the Staten Island borough of NYC. The collector area required for such a STS was determined to be less than the roof area of the building, making it architecturally feasible. The storage volume required to provide seasonal thermal storage with water is too large to be architecturally feasible. The storage volume required is 24% of the volume of the simplified case study building.

Chapter 6 proposes researching the potential for using the large volume of a crushed rock foundation located beneath the building as the thermal store. The use of a self-regulating layer of PCM between the thermal store and the building foundation slab would provide added thermally dense storage and regulation of thermal release from the storage to the building on a seasonal scale. The self-regulation of the release of thermal energy from the storage system to the building would be dependent on the cycling of the PCM from solid to liquid causing the PCM to spread across the boundary between the building slab and the thermal store inhibiting heat transfer. A compressible conductive layer is proposed as the mechanical driving force to ensure that the PCM returns to a reservoir as it melts. The interaction of these materials both physically and thermally will be crucial to the future work. A system of this type could provide seasonal storage that operates over a narrow temperature range, close to the level of human comfort. This would allow for more efficient collector operation and reduce stand-by losses from the TS to the surroundings. Locating the thermal store beneath the building prevents parts of the renewable energy system from being located outside of the building footprint and does not infringe on usable floor space within the building.

Providing architecturally and economically feasible seasonal thermal storage would make a significant impact on the design of net-zero energy buildings in higher latitudes with high water and space heating demands.

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APPENDIX A
Description of Alternative Software and Design Methods

This appendix provides a discussion of the advantages and disadvantages of various methods and software programs that can be used to design STS's. Relevant design methods include the Utilizability(ϕ) methods and the Utilizability, f-Chart ($\bar{\phi}$, f-Chart) Method. Software developed to study solar thermal systems include WATSUN 2009, SOLCHIPS, MINSUN, EnergyPlus, and the Transient Energy Simulation Tool (TRNSYS). Unlike the other software tools, TRNSYS can simulate a wide range of system configurations and has been expanded to other applications involving transient energy flows including building envelopes and systems. EnergyPlus is a software tool focused on the simulation of building envelopes and systems that can also simulate the performance of STS's. In addition to these software and design methods, researchers studying STS's often develop models using software like MATLAB, Excel with VisualBasic, or Engineering Equation Solver (EES) to perform calculations based on the equations governing the thermophysical behaviour of STS's. Not all of these methods and software tools are applicable to all types of solar thermal systems. The advantages and disadvantages of these methods and software are discussed with particular regard to their applicability to the design of a STS integrated within a NZE school in the NYC borough of Staten Island in this Appendix.

Duffie & Beckman (2006) credit Whillier (1953) with the first developments of the $\bar{\phi}$ design methods. The general concept of the utilizability of solar energy for producing thermal energy at a required temperature has undergone extensive research and development over the last six decades and remains relevant today, having seen revision by Karatasou, Santamouris, & Geros as recently as 2005. Fundamentally, the utilizability concept is a way of statistically analyzing radiation data, which can be used in specific cases to predict the performance of STS's. Utilizability analysis of STS performance is a powerful analysis tool due to the smaller number of calculations required when compared to a detailed simulation. However, utilizability methods still require more calculations than can reasonably be done by hand and have some important limitations that restrict their applicability to specific types of STS's. Duffie & Beckman (2006) note that the primary limitation to the utilizability methods is the necessity of knowing the temperature of the fluid entering the collector. This limitation is due to the dependence of collector performance on the temperature of the HTF entering the collector. In STS's with thermal storage the temperature of the HTF is dependent on the temperature of the thermal storage which is a function of the load on the system and the solar energy delivered to the thermal storage. This makes the utilizability methods well suited to STS that deliver water to the collectors from a source that is at a constant temperature or to STS's with very large storage volumes that have relatively stable temperatures (Duffie & Beckman, 2006). The $\bar{\phi}$ methods applicability to STS's with seasonal scale storage makes it an appropriate analysis tool for this thesis. However, the limitation to STS's with large storage capacities would necessitate the use of an additional analysis tool to predict the performance of systems with diurnal scale storage. The reduced number of calculations compared to a detailed simulation is also of diminished importance due to the high processor speeds of modern computers and the number of calculations would still require implementation in software like MATLAB or Excel. For these reasons the $\bar{\phi}$ method has not been selected as the primary analysis tool for this thesis.

Duffie & Beckman (2006) attributed Klein and Beckman with the combination of the utilizability concept and the f-Chart correlations to form the $\bar{\phi}$, f-Chart method. The f-Chart method provides correlations between two dimensionless variables and the monthly solar fraction based on the results from a large number of detailed simulations of common STS's. These correlations can be used to predict the annual SF for some of the most common STS designs. The f-Chart method is limited to systems that are able to use energy delivered near 20°C (Duffie & Beckman, 2006). The $\bar{\phi}$, f-Chart method incorporates the utilizability concepts into the f-Chart method through the reformulation of the dimensionless variables of the f-Chart method. The performance of a typical STS was simulated with varying values for the dimensionless variables and the storage capacity to develop a correlation between the dimensionless variables, the storage capacity, and the monthly solar fraction. The combination of the two methods creates a method that can be applied to energy demands with a wide range of minimum usable temperatures, an important limitation of the f-Chart method, and to systems with limited storage capacities, an important limitation of the $\bar{\phi}$ method (Duffie & Beckman, 2006). Due to its broad applicability to systems that do not have seasonal scale thermal storage, the $\bar{\phi}$, f-Chart method is potentially a useful design method for this thesis. However, use of the $\bar{\phi}$, f-Chart method would require the implementation of the $\bar{\phi}$, f-Chart method in MATLAB or Excel and the use of the $\bar{\phi}$ method or another analysis tool to obtain results for STS's with seasonal scale storage and has not been selected for implementation in this thesis.

Software programs that are capable of performing mathematical calculations and allow for logical programming structures can be used to develop models of STS's based on thermophysical equations describing the system components. MATLAB, Excel with VisualBasic, and Engineering Equation Solver (EES) are all possible tools for developing a model of a STS. These mathematics software tools are readily available and provide a relatively easy programming environment for the development of a STS model. The availability of these tools and the flexibility of creating a custom STS model that exactly meets the needs of this thesis are advantages of this approach. However, these advantages are outweighed by the significant time required to develop, debug, and validate this type of model.

The software programs MINSUN and SOLCHIPS were both developed originally as design tools intended to optimize central solar heating plants with seasonal storage (CSHPSS). Much of the development of MINSUN occured in Sweden (International Energy Agency, 1985), and SOLCHIPS was developed in Finland at the Helsinki University of Technology (Lund & Peltola, 1992). MINSUN was created as part of the International Energy Agencies (IEA) research on solar heating and cooling, specifically Task VII- Central Solar Heating Plants with Seasonal Storage (International Energy Agency, 1985). MINSUN developed into a tool that is capable of simulating a range of combinations of collectors, thermal storage methods, and auxiliary heating methods. The emphasis on seasonal storage and the ability to simulate systems with different components are strengths of MINSUN with regard to the goals of this thesis. However, despite use as a simulation tool as recently as 2007 (Nilsson, Hakansson, & Karlsson, 2007), MINSUN is not as readily available as some of the other software programs described in this section. SOLCHIPS was developed as a tool for rapidly designing and optimizing STS's with seasonal scale thermal storage. SOLCHIPS does not rely on equations describing the thermophysical behavior of the components of the STS being analyzed and is not capable of providing valid results for systems with non-seasonal scale storage. SOLCHIPS is not actively used by the community researching STS's as the most recent research using the program occurred in 1997 (Argiriou, 1997). The inaccessibility and age of these software tools are the justifications for not applying them in this research.

WATSUN 2009 is available for download from the website of Natural Resources Canada (Natural Resources Canada, 2011). The program has its own graphical user interface and is capable of modeling the performance of STS's with and without storage. WATSUN is user-friendly but is not capable of running parametric simulations or optimized solutions. The user must choose from a limited number of preconfigured STS's (Long & Wood, 1993). Due to these limitations, WATSUN is not well-suited to finding the range of collector area and storage volume combinations that will provide a reasonable range of solar fractions for the case study analyzed in this thesis.

The Transient Energy System Simulation Tool (TRNSYS) (TRNSYS, 2011) was first developed by Klein, Cooper, Freeman, Beekman, Beckman, and Duffie in 1975 (Duffie & Beckman, 2006). TRNSYS was originally developed for analyzing solar energy systems, and has been continually developed over the last 46 years with the most recent update released in July 2010 (University of Wisconsin, 2011). TRNSYS is now used for additional applications including analysis of building energy flows. The program is written in a modular format with subroutines that calculate the performance of typical components of solar energy systems (Duffie & Beckman, 2006). TRNSYS is an excellent research tool that has been shown to provide results closely matching measurements of the energy flows in functioning physical systems. Duffie & Beckman (2006) present the results of a study comparing the simulated results obtained from TRNSYS with measured values from a physical system, where the difference between the simulated and measured values were found to be within the range of uncertainty associated with the physical measurements. TRNSYS simulations were used in the development of both the f-Chart method (Haberl & Cho, 2004) and the ϕ, f-Chart method. As a well-developed commercially available research tool TRNSYS was deemed too complex and too costly for the purposes of this thesis, although it could be beneficial for more detailed design analysis.

EnergyPlus is a computer software tool for simulating the flow of energy within buildings. The tool is based on two older similar software tools, Building Load Analysis and System Thermodynamics (BLAST) and DOE-2. These tools were developed in the late 1970s and intended for use by building engineers and architects to assist in the design of buildings and building mechanical systems (U.S. Department of Energy, 2010d). Of the many improvements to the underlying algorithms of BLAST and DOE-2 implemented in EnergyPlus, the addition of renewable energy simulation capabilities is most pertinent to this thesis (Griffith & Ellis, 2004). The simulation of STS in EnergyPlus is based on the water storage tank models, HVAC connection methods, and the collector performance equations in Duffie & Beckman (2006), which are described in Section 3.2.2.3 (Griffith & Ellis, 2004). Results of STS simulations performed with EnergyPlus have been verified by comparison to TRNSYS simulations (Griffith & Ellis, 2004). EnergyPlus itself is essentially a calculation engine and does not have a graphical user-interface (U.S. Department of Energy, 2010d). Input to and output from EnergyPlus is done with text files, which makes it tedious to work with directly. However, there are many graphical interfaces available from third party developers that simplify creating input for EnergyPlus and analyzing the output. In addition to the graphical interfaces there is a wide-range of programming languages that can be used to automate the process of manipulating text based files. For parametric simulations EnergyPlus includes a parametric preprocessor, which can expand a single input file into multiple files for parametric simulations (U.S. Department of Energy, 2010c). Unlike many of the other software tools for studying the performance of STS's EnergyPlus is readily available, free, and undergoing active development. Due to the accessibility and ability to perform detailed parametric simulations, EnergyPlus was selected for simulating the performance of the STS's under consideration in this thesis.

APPENDIX B
Bash Shell Code

B.1 ePlusDesSpaceFunc.sh

```
#!/bin/bash

#================================================================
#========== SCRIPT TO RUN MULTIPLE PARAMETRIC SOLAR THERMAL
    SIMULATIONS USING E+ TO FIND DESIGN SPACE =====
#================================================================

# Script runs setArraySize.sh, paraVolSetup.sh, ePParaTemAdj.sh
    to produce results for
#plotting SF vs. (storage volume/collector area) curves

# Script then runs simulations to find the array size necessary
    to obtain a set SF at specified
# (storage volume/collector area) ratio. A parametric simulation
     is then performed wiht the new array size.


#TO RUN:
#Script should be run from file with a modified .idf file, .rvi
    file and any other supporting files
#necessary to run the E+ simulation

# ARGUMENT 1 ====  NAME OF THE WEATHER FILE WITH .epw EXTENSION
# ARGUMENT 2 ====  ANNUAL LOAD IN MWh
# ARGUMENT 3 ====  NUMBER OF PARAMETRIC RUNS
# ARGUMENT 4 ====  Ratio of storage volume to collector area for
     start of parametric runs
# ARGUMENT 5 ====  Ratio of storage volume to collector area for
     end of parametric runs

#NOTE: DIRECTORY CONTAINING .idf FILE SHOULD ALSO CONTAIN A .rvi
     FILE
#NOTE: THE .csv FILENAME INSIDE THE .rvi FILE SHOULD BE
    filenamecsv1.csv
#NOTE: PARAMETRIC IDF FILE MUST HAVE NUMERIC SUFFIX SPECIFIED
```

```
# The .idf file should contain the following search strings:
#==================================================

# Used in this script file:
#--------------------------------------------------
# sHELLtANKvOLUMEhEATER -on the TANK VOLUME line of the "
    WaterHeater:Mixed" object for the storage tank
# sHELLlOSScOEFFhEATER -on the OFF-CYCLE LOSS COEFFICIENT TO
    AMBIENT TEMPERATURE line of the "WaterHeater:Mixed" object
    for the storage tank
#                                          -also on the ON-CYCLE
     LOSS COEFFICIENT TO AMBIENT TEMPERATURE line of the "
    WaterHeater:Mixed" object for the storage tank
#--------------------------------------------------

# Used in setArraySize.sh:
#--------------------------------------------------
# sHELLcOLLECTORaREA -on the line within the Collector
    Performance Object with the gross area of the collector

# sHELLcOLLsHADEoBJECT -first line of shade object to be copied
    by setArraySize.sh
# sHELLcOLLECTORnAMEfLAG -on the NAME line of the "Shading:Site:
    Detailed" object for the collector
# sHELLcOLLECTOR1vERTEX1 -on the line with the first vertice
    coordinates
# sHELLcOLLECTOR1vERTEX2
# sHELLcOLLECTOR1vERTEX3
# sHELLcOLLECTOR1vERTEX4

# sHELLbRANCHlISTnAME -on the line with the collector branch
    within the BranchList Object for the collectors
# sHELLsPLITTERlISTnAME -on the line with the name of the
    splitter within the Connector:Splitter Object for the
    collectors
# sHELLmIXERlISTnAME -on the line with the name of the mixer
    within the Connector:Mixter Object for the collectors

# sHELLbRANCHbLOCKsTART -on the first line of the Branch Object
    for the collector
# sHELLbRANCHnAME -on the NAME line of the BRANCH object for the
     collector
# sHELLcOLLECTORcOMPONENT1nAME -on the COMPONENT NAME line of
    the "Branch" object for the collector
# sHELLcOMPONENT1iNLETnODEnAME -on the COMPONENT INLET NODE NAME
```

```
    line of the "Branch" object for the collector
# sHELLcOMPONENT1oUTLETnODEnAME -on the COMPONENT OUTLET NODE
    NAME line of the "Branch" object for the collector

# sHELLcOLLECTORnAME1 -on the NAME line of the "SolarCollector:
    FlatPlate:Water" object for the collector
# sHELLcOLLECTORsURFnAME1 -on the SURFACE NAME line of the "
    SolarCollector:FlatPlate:Water" object for the collector
# sHELLcOLLECTORiNLETnODEnAME1 -on the INLET NODE NAME line of
    the "SolarCollector:FlatPlate:Water" object for the collector
# sHELLcOLLECTORoUTLETnODEnAME1 -on the OUTLET NODE NAME line of
    the "SolarCollector:FlatPlate:Water" object for the
    collector
#---------------------------------------------------------------

# Used in paraVolSet.sh:
#---------------------------------------------------------------
# sHELLwATERhEATERmIXED -on the first line of the "WaterHeater:
    Mixed" object for the storage tank
# sHELLtANKvOLUMEhEATER -on the TANK VOLUME line of the "
    WaterHeater:Mixed" object for the storage tank
# sHELLlOSScOEFFhEATER -on the OFF-CYCLE LOSS COEFFICIENT TO
    AMBIENT TEMPERATURE line of the "WaterHeater:Mixed" object
    for the storage tank
#                                   -also on the ON-CYCLE
    LOSS COEFFICIENT TO AMBIENT TEMPERATURE line of the "
    WaterHeater:Mixed" object for the storage tank
#---------------------------------------------------------------

# Used in ePParaTempAdj.sh:
#---------------------------------------------------------------
# sHELLsTORAGEtANKsTARTtEMPERATURE -on the line within the Hot
    Water Setpoint Temp Schedule that sets the temperature for
    the first hour of the simulation
# EnergyPlus seems to set the storage tank temperature at the
    start of the simulation to the hot water setpoint for the
    beginning of the simulation
# NOTE: ePParaTempAdj.sh searches for a string of the form (.idf
    input name)1.csv on line two of the .rvi file
#---------------------------------------------------------------



# .rvi file should contain the following strings
#===============================================================
```

```
#Used in this script file:
#——————————————————————————————————————
# sHELLcSVnAME— on second line of .rvi to be replaced by names
    for the output .csv files
#——————————————————————————————————————



#======================================
#=================================================== CODE BELOW
    ==========
#===============================================

args=("$@")
. ./ePlusShellFuncLib.lib

echo "args0: ${args[0]}"
echo "args1: ${args[1]}"
echo "args2: ${args[2]}"
echo "args3: ${args[3]}"
echo "args4: ${args[4]}"

weatherFileName=${args[0]}

bigComment "Start of Script"
origIdfFile=$(ls *.idf)
origRviFile=$(ls *.rvi)
echo "Original Input .idf File Name:    $origIdfFile"
echo "Original Input .rvi File Name:    $origRviFile"

#==================================================================
#Calculates first guess for array size based on annual load
load=${args[1]}
arraySize=$(echo "scale=4; $load * 2" | bc)

echo "First guess Array Size:   $arraySize"


newDirFunc $arraySize

stripExtFunc $arraySize $origIdfFile
echo "Original .idf file without extension and array size prefix
    :  $inputNoExtension"

prepRviFunc $origRviFile 1
```

```
bigComment "FIRST_GUESS_PARAMETRIC_RUN"
#==================================================================
#Runs the setArraySize, paraVolSet, and ePParaTempAdj scripts to
    create curve

#Calls the script setArraySize.sh to set correct number of
   collectors in .idf file
bigComment "ENTERING_setArraySize.sh"
echo "Sending_Args:"
echo "arg1:_$origIdfFile"
echo "arg2:_$arraySize"
setArraySize.sh $origIdfFile $arraySize

#Calls the script paraVolSetup.sh to add E+ Parametric commands
   and values .idf file
bigComment "Param_Volume_Setup"
echo "arg1:_$arraySize$origIdfFile"
echo "arg2:_$arraySize"
echo "arg3:_${args[2]}"
echo "arg4:_${args[3]}"
echo "arg5:_${args[4]}"
paraVolSet.sh $arraySize$origIdfFile $arraySize ${args[2]} ${
   args[3]} ${args[4]}

#Calls the script ePParaTemAdj.sh to parametrically run .idf
   files
bigComment "Run_E+_Param"
echo "arg1:_$inputNoExtension"
echo "arg2:_${args[0]}"
echo "arg3:_${args[2]}"
ePParaTempAdj.sh $inputNoExtension ${args[0]} ${args[2]}


#==================================================================
bigComment "seekSfFunc_BOTTOM_CURVE_RUN"
seekSfFunc 2 ${args[2]} ${args[4]}

#==================================================================
#============================================= RUN PARA FOR BOTTOM
   ARRAY SIZE ===
#==================================================================
bigComment "BOTTOM_PARA_CURV_RUN"
#New directory for parametric simulations with new arraySize
newDirFunc para

#STRIPS THE EXTENSION FROM THE INPUT FILE FOR USE IN THE
```

```
    ePParaTemAdj SCRIPT
#Resets inputNoExtension variable and resets .rvi file
stripExtFunc $arraySize $origIdfFile
prepRviFunc $origRviFile 1

#CREATE CORRECT NUMBER OF SHADE OBJECTS, SPLITTER, MIXERS,
    BRANCHES AND COLLECTORS
bigComment "Collector .idf Setup"
echo "Sending Args:"
echo "arg1: $origIdfFile"
echo "arg2: $arraySize"
setArraySize.sh $origIdfFile $arraySize

#ADD PARAMETRIC VOLUME AND HEAT LOSS VALUES FOR STORAGE TANK
bigComment "Param Vol Setup"
echo "arg1: $arraySize$origIdfFile"
echo "arg2: $arraySize"
echo "arg3: ${args[2]}"
echo "arg4: ${args[3]}"
echo "arg5: ${args[4]}"
paraVolSet.sh $arraySize$origIdfFile $arraySize ${args[2]} ${
    args[3]} ${args[4]}

#CREATES .rvi FOR EACH PARAMETRIC RUN AND RUNS E+ FOR EACH
    PARAMETRIC RUN
#ALSO TESTS BEGINNING AND END OF YEAR TEMPERATURES OF STORAGE
    TANK AND REPEATES SIM IF THEY DIFFER
bigComment "Run E+ Param"
echo "arg1: $inputNoExtension"
echo "arg2: ${args[0]}"
echo "arg3: ${args[2]}"
ePParaTempAdj.sh $inputNoExtension ${args[0]} ${args[2]}








#=====================================================================
bigComment "seekSf RUN FOR HIGH CURVE"
cd ..
seekSfFunc 3 ${args[2]} ${args[4]}

#===================================================================
#================================================== RUN PARA FOR TOP
```

```
    ARRAY SIZE =======
#==============================================================

bigComment "RUN_PARA_FOR_HIGH_CURVE"
#New directory for parametric simulations with new arraySize
newDirFunc para

#STRIPS THE EXTENSION FROM THE INPUT FILE FOR USE IN THE
    ePParaTemAdj SCRIPT
#Resets inputNoExtension variable and resets .rvi file
stripExtFunc $arraySize $origIdfFile
prepRviFunc $origRviFile 1

#CREATE CORRECT NUMBER OF SHADE OBJECTS, SPLITTER, MIXERS,
    BRANCHES AND COLLECTORS
bigComment "Collector_.idf_Setup"
echo "Sending_Args:"
echo "arg1:_$origIdfFile"
echo "arg2:_$arraySize"
setArraySize.sh $origIdfFile $arraySize

#ADD PARAMETRIC VOLUME AND HEAT LOSS VALUES FOR STORAGE TANK
bigComment "Param_Vol_Setup"
echo "arg1:_$arraySize$origIdfFile"
echo "arg2:_$arraySize"
echo "arg3:_${args[2]}"
echo "arg4:_${args[3]}"
echo "arg5:_${args[4]}"
paraVolSet.sh $arraySize$origIdfFile $arraySize ${args[2]} ${
    args[3]} ${args[4]}

#CREATES .rvi FOR EACH PARAMETRIC RUN AND RUNS E+ FOR EACH
    PARAMETRIC RUN
#ALSO TESTS BEGINNING AND END OF YEAR TEMPERATURES OF STORAGE
    TANK AND REPEATES SIM IF THEY DIFFER
bigComment "Run_E+_Param"
echo "arg1:_$inputNoExtension"
echo "arg2:_${args[0]}"
echo "arg3:_${args[2]}"
ePParaTempAdj.sh $inputNoExtension ${args[0]} ${args[2]}
```

```
#==========================================================
bigComment "seekSf RUN FOR HIGHEST CURVE"
cd ..
seekSfFunc 4 ${args[2]} 0

#==========================================================
#============================================= RUN PARA FOR TOP
    ARRAY SIZE ===
#==========================================================

bigComment "RUN PARA FOR HIGHEST CURVE"
#New directory for parametric simulations with new arraySize
newDirFunc para

#STRIPS THE EXTENSION FROM THE INPUT FILE FOR USE IN THE
    ePParaTemAdj SCRIPT
#Resets inputNoExtension variable and resets .rvi file
stripExtFunc $arraySize $origIdfFile
prepRviFunc $origRviFile 1

#CREATE CORRECT NUMBER OF SHADE OBJECTS, SPLITTER, MIXERS,
    BRANCHES AND COLLECTORS
bigComment "Collector .idf Setup"
echo "Sending Args:"
echo "arg1: $origIdfFile"
echo "arg2: $arraySize"
setArraySize.sh $origIdfFile $arraySize

#ADD PARAMETRIC VOLUME AND HEAT LOSS VALUES FOR STORAGE TANK
bigComment "Param Vol Setup"
echo "arg1: $arraySize$origIdfFile"
echo "arg2: $arraySize"
echo "arg3: ${args[2]}"
echo "arg4: ${args[3]}"
echo "arg5: ${args[4]}"
paraVolSet.sh $arraySize$origIdfFile $arraySize ${args[2]} ${
    args[3]} ${args[4]}

#CREATES .rvi FOR EACH PARAMETRIC RUN AND RUNS E+ FOR EACH
    PARAMETRIC RUN
#ALSO TESTS BEGINNING AND END OF YEAR TEMPERATURES OF STORAGE
    TANK AND REPEATES SIM IF THEY DIFFER
bigComment "Run E+ Param"
echo "arg1: $inputNoExtension"
echo "arg2: ${args[0]}"
```

```
echo "arg3:␣${args[2]}"
ePParaTempAdj.sh $inputNoExtension ${args[0]} ${args[2]}
```

B.2 ePlusShellFuncLib.lib

```
# ePlusShellFuncLib.lib

# VARIABLES
arraySize=0
origIdfFile=input
origRviFile=input
weatherFileName=blankName
inputNoExtension=blankNameTwo

# FUNCTIONS
#==========================================================
#Borrowed from runenergplus script in EnergyPlus bin folder
function set_ep_dir () {
        U_DIR=`pwd`
        if [ -n "`readlink "$0"`" ]; then
                S_DIR=$(cd "$(dirname "$(readlink "$0")")"; pwd)
                cd "$U_DIR"
        else
                S_DIR=$(cd "$(dirname "$0")"; pwd)
                cd "$U_DIR"
        fi
        ENERGYPLUS_DIR=`dirname "$S_DIR"`
}

#==========================================================
bigComment ()
{
echo
echo
echo "*********************************************"
echo "************  "${1}"  **************"
echo "*********************************************"
echo
}

#==========================================================
litComment ()
{
echo "************  "${1}"  **************"
}

#==========================================================
newDirFunc ()
{
```

```
        mkdir ${1}
        cp ./* ${1}
        cd ${1}
}

#==================================================================
stripExtFunc ()
{
mkfile -n 10 noExtension #MAKES BLANK FILE

ed -s noExtension <<EOF
H
i
${1}${2}
.
w
q
EOF


idfExtTest=$(awk -F. '/idf/ {print $2}' noExtension)
echo "idfExtTest:␣$idfExtTest"
if [ "$idfExtTest" != "idf" ]; then
        inputNoExtension=$(awk -F. '/idf/ {print $1"."$2}'
           noExtension)
        echo "inputNoExtension:␣$inputNoExtension"
else
        inputNoExtension=$(awk -F. '/idf/ {print $1}'
           noExtension)
        echo "inputNoExtension:␣$inputNoExtension"
fi

rm noExtension
}


#==================================================================
prepRviFunc ()
{
if [ "${2}" != "" ]; then
cp $1 $inputNoExtension"-"${2}".rvi"
ed -s $inputNoExtension"-"${2}".rvi" <<EOF
H
/sHELLcSVnAME/
s/sHELLcSVnAME/$inputNoExtension${2}.csv/
w
```

```
q
EOF
else
cp $1 $inputNoExtension".rvi"
ed -s $inputNoExtension".rvi" <<EOF
H
/sHELLcSVnAME/
s/sHELLcSVnAME/$inputNoExtension.csv/
w
q
EOF
fi
}

#==============================================================
seekSfFunc ()
{
#================================== FILE FOR SEEKING A SOLAR FRACTION
    USING E+ SIMS =====
# ARGUMENT 1 ==== TYPE OF RUN: 1 -Seek given solar fraction at
    given storage volume/collector area ratio;
#                              2 -Seek solar fraction for
    maximum storage volume/collector area ratio from parametric
    run that is
#                                10% above solar fraction for
    minimum storage volume/collector area ratio;
#                              3 -Seek solar fraction of 1 for
    maximum storage volume/collector from parametric run
#                                                          4 -
    Seek solar fraction of 1 for volume/collector of 1
# ARGUMENT 2 ==== IF ARG 1 == 1 THEN: solar fraction to seek
#                 IF ARG 1 == 2,3, or 4 THEN: number of
    parametric runs
# ARGUMENT 3 ==== IF ARG 1 == 1 THEN: storage volume/collector
    area ratio
#                 IF ARG 1 == 2 or 3 THEN: ${args[4]} of
    ePlusSTSDesSpace.sh, which is the ending storage volume/
    collector area ratio
#                                IF ARG 1 == 4 THEN: value of 0
     (not used because volume/collector area ratio=1
#=========================================================
```

```
#==================================================================
#Determines how script is to run find array size for bottom
   curve, top curve or given SF
if [ "$1" -eq "1" ]; then
        sfGoal=$2
        tankColRatio=$3
        echo
        echo "************* USER INPUT FOR SFGOAL AND TANK/COL
           RATIO ****************"
        echo "seek sf: $sfGoal"
        echo "for ratio: $tankColRatio"
        echo "******************************************"
        echo
        newDirFunc arrayArea
elif [ "$1" -eq "2" ]; then
        #Determines solar fraction for largest and smallest
           volume from last parametric runs
        minSF=$(sf.sh $inputNoExtension 1)
        maxSF=$(sf.sh $inputNoExtension $2)
        #Set goal solar fraction
        sfGoal=$(echo "scale=4; $minSF + 0.10" | bc)
        tankColRatio=$3
        SF=$maxSF
        ifClauseOld=1
        echo "************* SFGOAL AND TANK/COL RATIO BASED ON
           PARA RESULTS FOR MIN CURVE ****************"
        echo "Min SF:   $minSF"
        echo "Max SF:   $maxSF"
        echo "SF Goal: $sfGoal"
        echo "for ratio: $tankColRatio"
        echo "ifClause old: $ifClauseOld"
        echo "******************************************"
        echo
        cd .. #Back to working directory
        newDirFunc arrayAreaBottomCurve
elif [ "$1" -eq "3" ]; then
        sfGoal=1
        tankColRatio=$3
        ifClauseOld=1
        echo "************* SFGOAL AND TANK/COL RATIO BASED ON
           PARA RESULTS FOR MAX CURVE ****************"
        echo "SF Goal: $sfGoal"
        echo "for ratio: $tankColRatio"
        echo "ifClause old: $ifClauseOld"
        echo "******************************************"
        echo
```

```
        cd .. #Back to working directory
        newDirFunc arrayAreaHighCurve
elif [ "$1" -eq "4" ]; then
        sfGoal=1
        tankColRatio=1
        ifClauseOld=1
        echo "************* SFGOAL AND TANK/COL RATIO BASED ON 
            PARA RESULTS FOR MAX CURVE ****************"
        echo "SF Goal: $sfGoal"
        echo "for ratio: $tankColRatio"
        echo "ifClause old: $ifClauseOld"
        echo "*****************************************"
        echo
        cd .. #Back to working directory
        newDirFunc arrayAreaHighestCurve
else
        echo "ERROR: argument 2 counting from zero must be 
            1,2,3, or 4"
        exit
fi

#=================================================
#Make new directory for output of finding array size



#=================================================
#Increases or decreases array size and repeats simulation until
    SF is close to goal SF
stepSize=$(echo "scale=4; $arraySize / 2" | bc)
sfTestVal=0
guessCount=1

while [ $sfTestVal -ne 1 ]; do
#SETS arraySize TO NEW VALUE
echo "************ BEGINNING OF LOOP ************"
echo "SF:        $SF"
echo "sfGoal:  $sfGoal"
echo "arraySize: $arraySize"
echo "stepSize:  $stepSize"
echo "*****************************************"
echo
set $(awk -F, -v SF=$SF -v sfGoal=$sfGoal -v arraySize=
    $arraySize -v stepSize=$stepSize '
        BEGIN {
                if(SF-sfGoal>0) {
```

```
                                arraySize=arraySize-stepSize;
                                print arraySize;
                                print 0
                                }
                        else {
                                arraySize=arraySize+stepSize;
                                print arraySize;
                                print 1
                                }
        }')
arraySize=$1
ifClauseNew=$2
echo "************ ARRAY SIZE ***************"
echo "arraySize:  $arraySize"
echo "ifClause:   $ifClauseNew"
echo "****************************************"
echo

if [ $ifClauseNew -ne $ifClauseOld ]; then
ifClauseOld=$ifClauseNew
stepSize=$(echo "scale=4; $stepSize / 2" | bc)
echo
echo "************ ifClause NEW OLD COMP ***************"
echo "CHANGE IN STEP SIZE"
echo "new stepSize: $stepSize"
echo "****************************************"
echo
else
echo
echo "************ ifClause NEW OLD COMP ***************"
echo "NO CHANGE IN STEP SIZE"
fi

#Copy setup files to new directory for new array size and move
    to it
newDirFunc $guessCount"-"$arraySize
echo
echo "MOVED TO NEW DIRECTORY"
echo

guessCount=$(echo "scale=1; $guessCount + 1" | bc)
if [ "$guessCount" -gt 30 ]; then
        echo "ERROR: Too many loops in the seekSfFunc"
        exit
fi
```

```
#Resets inputNoExtension variable and resets .rvi file
bigComment "LOOK_HERE"
echo "inputNoExtension: $inputNoExtension"
echo "arraySize: $arraySize"
echo "origIdfFile: $origIdfFile"
echo
echo "************ CALLING stripExtFunc *************"
stripExtFunc $arraySize $origIdfFile
echo "inputNoExtension: $inputNoExtension"
echo "*******************************************"
echo
echo "************ CALLING prepRviFunc *************"
prepRviFunc $origRviFile
echo "*******************************************"
echo

bigComment "Collector .idf Setup"
#Calls the script setArraySize.sh to set correct number of
    collectors in .idf file
setArraySize.sh $origIdfFile $arraySize

bigComment "Volume Setup"
echo $arraySize$origIdfFile

awk -F, -v VAR=$arraySize -v tCRatio=$tankColRatio '
        /sHELLtANKvOLUMEhEATER/ {
                volume=VAR*tCRatio
                printf("    %5.2f,              !- 
                   ShellTankVolHeater\n",volume)
                }

        /sHELLlOSScOEFFhEATER/ {
                uaTankVol = tCRatio * VAR
                logTankVol = log(uaTankVol)
                insThick = 21.404 * exp(logTankVol * 0.3619)
                uValue = 1/(0.0004375 + ((insThick/1000)/0.02) +
                    0.23)
                logHeight = log((36 * uaTankVol) / ( 3.14159))
                height = exp(logHeight * (0.3333333))
                radius = height/6
                surfArea = (2 * 3.14159 * height * (radius +
                   0.007 + (insThick/1000))) + (2 * 3.14159 * (
                   radius + 0.007 + (insThick/1000)) * (radius +
                    0.007 + (insThick/1000)))
                uaValue = surfArea * uValue
```

```
                    printf("%10.6f,␣␣␣␣!−␣\n",uaValue);
                    }

  !/(sHELLtANKvOLUMEhEATER)|(sHELLlOSScOEFFhEATER)/ {
                    print
                    }' $arraySize$origIdfFile >
                       TEMP_$arraySize$origIdfFile

rm $arraySize$origIdfFile
mv TEMP_$arraySize$origIdfFile $arraySize$origIdfFile


bigComment "Run␣E+"
#Run E+ and check beginning and ending tank temps if they need
   to be corrected
echo "=============␣inputNoExtension:␣␣␣$inputNoExtension"
ePlusTempAdj.sh $inputNoExtension $weatherFileName

bigComment "Eval␣E+␣Results"
#Get solar fraction for first and last sim (smallest and largest
    tank vol)
SF=$(sf.sh $inputNoExtension)
echo "SF:␣␣␣␣␣␣␣$SF"

#Test to see if the SF is close enough to exit while loop
set $(awk -F, -v SF=$SF -v sfGoal=$sfGoal '
        BEGIN {
                    if(SF-sfGoal>=0) {
                            testVal=SF-sfGoal;
                            }
                    else {
                            testVal=(SF-sfGoal)*-1;
                            }
                    if(testVal<0.05) {
                            print 1;
                            }
                    else {
                            print 0;
                            }
        }')
sfTestVal=$1
echo "sfTestVal␣$sfTestVal"
echo "current␣array␣Size:␣␣␣␣␣␣␣$arraySize"

#Back to array size finding directory
cd ..
```

done
}

B.3 setArraySize.sh

```
#!/bin/bash

#========== FILE FOR SETTING MULTIPLYING COLLECTORS TO NUMBER
    REQUIRED FOR ARRAY AREA ===
# ARGUMENT 1 ====  E+ FILENAME WITH .idf EXTENSION
# ARGUMENT 2 ====  ARRAY AREA


# .idf should contain the following search strings:
#------------------------------------------------------------
# sHELLcOLLECTORaREA -on the line within the Collector
    Performance Object with the gross area of the collector

# sHELLcOLLsHADEoBJECT -first line of shade object to be copied
    by setArraySize.sh
# sHELLcOLLECTORnAMEfLAG -on the NAME line of the "Shading:Site:
    Detailed" object for the collector
# sHELLcOLLECTOR1vERTEX1 -on the line with the first vertice
    coordinates
# sHELLcOLLECTOR1vERTEX2
# sHELLcOLLECTOR1vERTEX3
# sHELLcOLLECTOR1vERTEX4

# sHELLbRANCHlISTnAME -on the line with the collector branch
    within the BranchList Object for the collectors
# sHELLsPLITTERlISTnAME -on the line with the name of the
    splitter within the Connector:Splitter Object for the
    collectors
# sHELLmIXERlISTnAME -on the line with the name of the mixer
    within the Connector:Mixter Object for the collectors

# sHELLbRANCHbLOCKsTART -on the first line of the Branch Object
    for the collector
# sHELLbRANCHnAME -on the NAME line of the BRANCH object for the
      collector
# sHELLcOLLECTORcOMPONENT1nAME -on the COMPONENT NAME line of
    the "Branch" object for the collector
# sHELLcOMPONENT1iNLETnODEnAME -on the COMPONENT INLET NODE NAME
      line of the "Branch" object for the collector
# sHELLcOMPONENT1oUTLETnODEnAME -on the COMPONENT OUTLET NODE
    NAME line of the "Branch" object for the collector

# sHELLcOLLECTORnAME1 -on the NAME line of the "SolarCollector:
    FlatPlate:Water" object for the collector
```

```
# sHELLcOLLECTORsURFnAME1 -on the SURFACE NAME line of the "
    SolarCollector:FlatPlate:Water" object for the collector
# sHELLcOLLECTORiNLETnODEnAME1 -on the INLET NODE NAME line of
    the "SolarCollector:FlatPlate:Water" object for the collector
# sHELLcOLLECTORoUTLETnODEnAME1 -on the OUTLET NODE NAME line of
     the "SolarCollector:FlatPlate:Water" object for the
    collector
#=====================================================================

#Sets user terminal input in array
args=("$@")
arrayArea=${args[1]}

echo "RECEIVED ARGS:"
echo "ARG0 origIdffile: ${args[0]}"
echo "ARG1 arrayArea: ${args[1]}"

#Determines dimensions of collectors for spacing collectors
vert1x=$(awk -F, '/sHELLcOLLECTOR1vERTEX1/ {vert1x=$1}; END {
   printf "%05.12f",vert1x}' "${args[0]}")
vert3x=$(awk -F, '/sHELLcOLLECTOR1vERTEX4/ {vert3x=$1}; END {
   printf "%05.12f",vert3x}' "${args[0]}")
echo
echo "vert1x: $vert1x"
echo "vert3x: $vert3x"

#Determines number of collector required for array area by
   finding the gross area of each collector as defined in .idf
set $( awk -F, -v VAR=$arrayArea '
        /sHELLcOLLECTORaREA/{             #.idf file must have
            comment in line with gross area of collector "
            sHELLcOLLECTORaREA"
                colArea = $1
                }
        END {
                numCol = VAR/colArea
                printf("%5.0f", numCol)
        }' ${args[0]})
numCol=$1
if [ "$?" -ne "0" ]; then
        echo
        echo "ERROR: problem in 1st awk"
fi
echo "numCol:   $numCol"

#Determines where the shade surface definitions for the
```

```
    collectors to be multiplied begin and ends
set $(awk -F, '
        /sHELLcOLLsHADEoBJECT/ {
                shSurfBlockStart = NR
                }
        END {
                print shSurfBlockStart
                shSurfBlockEnd = shSurfBlockStart + 8
                print shSurfBlockEnd
                shSurfBlockEndSpace = shSurfBlockStart + 9
                print shSurfBlockEndSpace
        }' ${args[0]})
shSurfBlockStart=$1
shSurfBlockEnd=$2
shSurfBlockEndSpace=$3
if [ "$?" -ne "0" ]; then
        echo
        echo "ERROR: problem in 2nd awk"
fi
#echo "start: $shSurfBlockStart"
#echo "end: $shSurfBlockEnd"
#echo "endSpace: $shSurfBlockEndSpace"

#COPIES ORIGINAL INPUT FILE TO PRESERVE IT UNCHANGED
cp ${args[0]} FINISHED${args[0]}

#THIS BLOCK COPIES THE ENTIRE SHADING SURFACE OBJ DESCRIPTION
    THE SPECIFIED NUMBER OF TIMES W/O CHANGES
count=1
while [ $count -lt $numCol ]; do
        ed -s FINISHED${args[0]} <<-EOF
                H
                $shSurfBlockStart , $shSurfBlockEnd t
                    $shSurfBlockEndSpace
                w
                q
        EOF
        if [ "$?" -ne "0" ]; then
                echo
                echo "ERROR: problem in $count loop of copy shad
                    surf block"
        fi
        let count++
#       echo "number of collectors: $count"
done
```

```
count=1
while [ $count -lt $numCol ]; do
ed -s FINISHED${args[0]} <<EOF
H
/sHELLbRANCHlISTnAME/
a
    Collector 1 Branch,          !- sHELLbRANCHlISTnAME
.
/sHELLsPLITTERlISTnAME/
a
    Collector 1 Branch,          !- sHELLsPLITTERlISTnAME
.
/sHELLmIXERlISTnAME/
a
    Collector 1 Branch,          !- sHELLmIXERlISTnAME
.
w
q
EOF
if [ "$?" -ne "0" ]; then
        echo
        echo "ERROR: problem in $count loop of branch, splitter,
           mixer copy"
fi
let count++
#echo "number of collectors: $count"
done

#Determines where the shade surface definitions for the
   collectors to be multiplied begin and ends
set $(awk -F, '
        /sHELLbRANCHbLOCKsTART/ {
                BranchBlockStart = NR
                }
        END {
                print BranchBlockStart
                BranchBlockEnd = BranchBlockStart + 17
                print BranchBlockEnd
                BranchBlockEndSpace = BranchBlockStart + 18
                print BranchBlockEndSpace
        }' FINISHED${args[0]})
BranchBlockStart=$1
BranchBlockEnd=$2
BranchBlockEndSpace=$3
```

```
if [ "$?" -ne "0" ]; then
        echo
        echo "ERROR: problem in finding branch block location"
fi
#echo "start: $BranchBlockStart"
#echo "end: $BranchBlockEnd"
#echo "endSpace: $BranchBlockEndSpace"

#THIS BLOCK COPIES THE COLLECTOR BRANCH AND OBJ ENTIRE SHADING
   SURFACE OBJ DESCRIPTION THE SPECIFIED NUMBER OF TIMES W/O
   CHANGES
count=1
while [ $count -lt $numCol ]; do
        ed -s FINISHED${args[0]} <<-EOF
                H
                $BranchBlockStart , $BranchBlockEnd t
                   $BranchBlockEndSpace
                w
                q
        EOF
        if [ "$?" -ne "0" ]; then
                echo
                echo "ERROR: problem in $count loop of copy
                   branch block"
        fi
        let count++
#       echo "number of collectors: $count"
done


#exit


#THIS BLOCK OF CODE REPLACES THE COLLECTOR NAME WITH A
   NUMERICALLY ITERATED NAME AND ITERATES THE VERTICE VALUES
awk -F, -v numCol=$numCol -v vert1x=$vert1x -v vert3x=$vert3x '
BEGIN {
        surfCount = 0; vert2x = vert1x; vert4x = vert3x
        spacing = vert3x - vert1x + 0.25
        vertOneCount = 0; vertTwocount 0; vertThreeCount = 0;
           vertFourCount = 0; sblName = 0; sslName = 0; smlName
           = 0
        }

/sHELLcOLLECTORnAMEfLAG/ {
        surfCount = surfCount + 1
```

```
        printf("␣␣␣␣␣␣␣␣Collector␣Surface␣%i,␣␣␣␣␣␣␣␣␣␣␣␣␣!−␣
           Collector␣%i␣Surface␣Name\n",surfCount,surfCount)
        }

/sHELLcOLLECTOR1vERTEX1/ {
        vertOneCount = vertOneCount + 1
        printf("␣␣␣␣%3.12f,%3.12f,%3.12f,␣␣␣␣␣␣␣!−X,Y,Z␣==>␣
           Collector␣%i␣Vertex␣1\n",vert1x,$2,$3,vertOneCount)
        vert1x = vert1x + spacing
        }

/sHELLcOLLECTOR1vERTEX2/ {
        vertTwoCount = vertTwoCount + 1
        printf("␣␣␣␣%3.12f,%3.12f,%3.12f,␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣!−X,Y,Z␣
           ==>␣Collector␣%i␣Vertex␣2\n",vert2x,$2,$3,
           vertTwoCount)
        vert2x = vert2x + spacing
        }

/sHELLcOLLECTOR1vERTEX3/ {
        vertThreeCount = vertThreeCount + 1
        printf("␣␣␣␣%3.12f,%3.12f,%3.12f,␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣!−X,Y,Z␣
           ==>␣Collector␣%i␣Vertex␣3\n",vert3x,$2,$3,
           vertThreeCount)
        vert3x = vert3x + spacing
        }

/sHELLcOLLECTOR1vERTEX4/{
        vertFourCount = vertFourCount + 1
        printf("␣␣␣␣%3.12f,%3.12f,%3.12f;␣␣␣␣␣␣␣␣␣␣␣␣␣␣␣!−X,Y,Z␣
           ==>␣Collector␣%i␣Vertex␣4\n",vert4x,$2,$3,
           vertFourCount)
        vert4x = vert4x + spacing
        }

/sHELLbRANCHlISTnAME/ {
        sblName = sblName + 1
        printf("␣␣␣␣Collector␣%i␣Branch,␣␣␣␣␣␣␣␣␣␣!−␣Collector␣
           Branch␣Name␣%i\n",sblName,sblName)
        }

/sHELLsPLITTERlISTnAME/ {
        sslName = sslName + 1
        if (sslName < numCol) printf("␣␣␣␣Collector␣%i␣Branch,␣␣
           ␣␣␣␣␣␣␣␣!−␣Collector␣Branch␣Name␣%i\n",sslName,
           sslName);
```

```
        else if (sslName == numCol) printf("    Collector %i 
            Branch;         !- Collector Branch Name %i\n",sslName
            ,sslName);
        }

/sHELLmIXERlISTnAME/ {
        smlName = smlName + 1
        if (smlName < numCol) printf("    Collector %i Branch,  
                      !- Collector Branch Name %i\n",smlName,
            smlName);
        else if (smlName == numCol) printf("    Collector %i 
            Branch;              !- Collector Branch Name %i\n",
            smlName,smlName);
        }

/sHELLhOTnODEnAME/ {
        printf("    Collector %i Outlet Node,  !- Hot Node Name\n
            ",numCol)
        }

!/(sHELLcOLLECTORnAMEfLAG)|(sHELLcOLLECTOR1vERTEX1)|(
    sHELLcOLLECTOR1vERTEX2)|(sHELLcOLLECTOR1vERTEX3)|(
    sHELLcOLLECTOR1vERTEX4)|(sHELLbRANCHlISTnAME)|(
    sHELLsPLITTERlISTnAME)|(sHELLmIXERlISTnAME)|(sHELLhOTnODEnAME
    )/ {
        print
        }' FINISHED${args[0]} > TEMP_FINISHED${args[0]}

if [ "$?" -ne "0" ]; then
        echo
        echo "ERROR: problem in shad surf incremented 
            replacement"
fi

#Deletes original file and changes name of TEMP file to name of
    original file
rm FINISHED${args[0]}
mv TEMP_FINISHED${args[0]} FINISHED${args[0]}



awk 'BEGIN {colCompName = 0; colCompInNode = 0; colCompOutNode =
     0; colName = 0; colSurfName = 0; colNNN = 0; colONN = 0;
    sbName = 0}
/sHELLbRANCHnAME/ {
        sbName = sbName + 1
```

```
        printf("    Collector %i Branch,                 !- Collector Branch Name %i\n",sbName,sbName)
        }

/sHELLcOLLECTORcOMPONENT1nAME/ {
        colCompName = colCompName + 1
        printf("    Collector %i,                !- Collector Component %i Name\n",colCompName,colCompName)
        }

/sHELLcOMPONENT1iNLETnODEnAME/ {
        colCompInNode = colCompInNode + 1
        printf("    Collector %i Inlet Node,     !- Collector Component %i Inlet Node Name\n",colCompInNode,
            colCompInNode)
        }

/sHELLcOMPONENT1oUTLETnODEnAME/ {
        colCompOutNode = colCompOutNode + 1
        printf("    Collector %i Outlet Node,    !- Collector Component %i Outlet Node Name\n",colCompOutNode,
            colCompOutNode)
        }

/sHELLcOLLECTORnAME1/ {
        colName = colName + 1
        printf("    Collector %i,                    !- Collector Name %i\n",colName,colName)
        }

/sHELLcOLLECTORsURFnAME1/ {
        colSurfName = colSurfName + 1
        printf("    Collector Surface %i,          !- Collector Surf Name %i\n",colSurfName,colSurfName)
        }

/sHELLcOLLECTORiNLETnODEnAME1/ {
        colNNN = colNNN + 1
        printf("    Collector %i Inlet Node,      !- Collector Inlet Node Name %i\n",colNNN,colNNN)
        }

/sHELLcOLLECTORoUTLETnODEnAME1/ {
         colONN =  colONN + 1
         printf("   Collector %i Outlet Node,     !- Collector Outlet Node Name %i\n",colONN,colONN)
```

```
        }

 !/(sHELLbRANCHnAME)|(sHELLcOLLECTORcOMPONENT1nAME)|(
    sHELLcOMPONENT1iNLETnODEnAME)|(sHELLcOMPONENT1oUTLETnODEnAME
    )|(sHELLcOLLECTORnAME1)|(sHELLcOLLECTORsURFnAME1)|(
    sHELLcOLLECTORiNLETnODEnAME1)|(sHELLcOLLECTORoUTLETnODEnAME1
    )/ {
        print
        }' FINISHED${args[0]} > $arrayArea${args[0]}
if [ "$?" -ne "0" ]; then
        echo
        echo "ERROR:␣problem␣in␣branch␣block␣incremented␣
            replacement"
fi
```

B.4 paraVolSet.sh

```
#!/bin/bash

#========= FILE FOR SETTING MULTIPLYING COLLECTORS TO NUMBER
    REQUIRED FOR ARRAY AREA =====
# ARGUMENT 1 === E+ FILENAME WITH .IDF EXTENSION AND ARRAY SIZE
    PREFIX EX: 120input.idf
# ARGUMENT 2 === ARRAY SIZE
# ARGUMENT 3 === NUMBER OF PARAMETRIC SIMULATIONS DESIRED (TANK
    VOLUME AND HEAT LOSS COEFF BEING THE VARIABLE PARAMETERS)
# ARGUMENT 4 === STARTING RATIO OF STORAGE TANK VOLUME/COLLECTOR
     AREA (m^3/m^2) FOR PARAMETRIC SIMULATIONS
# ARGUMENT 5 === ENDING RATIO OF STORAGE TANK VOLUME/COLLECTOR
    AREA (m^3/m^2) FOR PARAMETRIC SIMULATIONS
# NOTE: Recommended range for arguments 4 & 5 is 0.001 to 10
    below 0.001 is essentially equivalent to no storage
# and above 0.5 is entering seasonal scale storage
# NOTE: Argument 5 must be greater than argument 4


# The .idf should contain the following search strings:
#------------------------------------
# sHELLwATERhEATERmIXED -on the first line of the "WaterHeater:
    Mixed" object for the storage tank
# sHELLtANKvOLUMEhEATER -on the TANK VOLUME line of the "
    WaterHeater:Mixed" object for the storage tank
# sHELLlOSScOEFFhEATER -on the OFF-CYCLE LOSS COEFFICIENT TO
    AMBIENT TEMPERATURE line of the "WaterHeater:Mixed" object
    for the storage tank
#                                          -also on the ON-CYCLE
     LOSS COEFFICIENT TO AMBIENT TEMPERATURE line of the "
    WaterHeater:Mixed" object for the storage tank
#
# This script inserts and replaces the following strings (THEY
    DO NOT NEED TO BE IN THE .idf!):
# sHELLtANKvOLUME
# sHELLlOSScOEFF
# sHELLnUMERICsUFFIX
#====================================




args=("$@")
```

```
numOfParam=${args[2]}
echo "numOfParam: $numOfParam"

#======================================
#Function to insert parametric heading
paramHeadFunc ()
{
ed -s ${args[0]} <<EOF
H
/sHELLwATERhEATERmIXED/
i
${1},
${2},                         !- Parameter Name
.
w
q
EOF
}

paramHeadFunc "Parametric:SetValueForRun" \$volHeatr

#================================
#Function to insert parametric text placeholder for replacement
    by numeric value later
placeHoldFunc ()
{
count=1
while [ "$count" -le "$numOfParam" ]; do
ed -s ${args[0]} <<EOF
H
/sHELLwATERhEATERmIXED/
i
${1}
.
w
q
EOF
let count++
done

ed -s ${args[0]} <<EOF
H
/sHELLwATERhEATERmIXED/
i

.
```

```
w
q
EOF
}

placeHoldFunc "sHELLtANKvOLUME"


#==================================
paramHeadFunc "Parametric:SetValueForRun" \$lossCoefHeatr
placeHoldFunc "sHELLlOSScOEFF"

#==================================
paramHeadFunc "Parametric:FileNameSuffix" "suffix"
placeHoldFunc "sHELLnUMERICsUFFIX"


awk -F, '
        /sHELLtANKvOLUMEhEATER/ {
                printf("    =$volHeatr,                  !- Tank
                    Volume {m3}\n")
        }

        /sHELLlOSScOEFFhEATER/ {
                printf("    =$lossCoefHeatr,              !-
                    Heater Loss Coefficient\n")
        }

        !/(sHELLtANKvOLUMEhEATER)|(sHELLlOSScOEFFhEATER)/ {
                print
                }' ${args[0]} > TEMP_${args[0]}

rm ${args[0]}
mv TEMP_${args[0]} ${args[0]}



awk -F, -v VAR=${args[1]} -v endLoop=$numOfParam -v startCount=$
    {args[3]} -v endCount=${args[4]} -v steps=$numOfParam '
BEGIN {
        steps=steps-1
        st=log(startCount*10000)/log(10)
        en=log(endCount*10000)/log(10)
        span=en-st
        step=span/steps
        sTVol = st; logTen = log(10); uaCount = st; volCount =
```

```
        1; lossCount = 1; suffixCount = 1
    }

/sHELLtANKvOLUME/ {
    expTenStep = exp(logTen * sTVol)
    tankVol = (expTenStep/10000) * VAR
    if (volCount < endLoop) printf("%10.8f,\n",tankVol);
    else if (volCount == endLoop) printf("%10.8f;␣␣!-␣
        sHELLlASTtANKvOLUME\n",tankVol);
    sTVol = sTVol + step
    volCount = volCount + 1
    }

/sHELLlOSScOEFF/ {
    uaExpTenStep = exp(logTen * uaCount)
    uaTankVol = (uaExpTenStep/10000) * VAR
    logTankVol = log(uaTankVol)
    insThick = 21.404 * exp(logTankVol * 0.3619)
    uValue = 1/(0.0004375 + ((insThick/1000)/0.02) + 0.23)
    logHeight = log((36 * uaTankVol) / ( 3.14159))
    height = exp(logHeight * (0.3333333))
    radius = height/6
    surfArea = (2 * 3.14159 * height * (radius + 0.007 + (
        insThick/1000))) + (2 * 3.14159 * (radius + 0.007 + (
        insThick/1000)) * (radius + 0.007 + (insThick/1000)))
    uaValue = surfArea * uValue
    if (lossCount < endLoop) printf("%10.6f,␣␣␣␣\n",uaValue)
        ;
    else if (lossCount == endLoop) printf("%10.6f;␣␣␣\n",
        uaValue);
    uaCount = uaCount + step
    lossCount = lossCount + 1
    }

/sHELLnUMERICsUFFIX/ {
    if (suffixCount < endLoop) printf("%2.0f,␣␣\n",
        suffixCount);
    else if (suffixCount == endLoop) printf("%2.0f;␣␣␣␣\n",
        suffixCount);
    suffixCount = suffixCount + 1
    }

!/(sHELLlOSScOEFF)|(sHELLtANKvOLUME)|(sHELLnUMERICsUFFIX)/ {
    print
    }' ${args[0]} > TEMP_${args[0]}
```

```
rm ${args[0]}
mv TEMP_${args[0]} ${args[0]}
```

B.5 ePParaTempAdj.sh

```
#!/bin/bash

#========== FILE FOR BATCH PROCESSING PARAMETRIC E+ FILES =====
# ARGUMENT 1 ====  E+ PARAMETRIC FILENAME WITHOUT .idf EXTENSION
# ARGUMENT 2 ====  NAME OF THE WEATHER FILE WITH .epw EXTENSION
# ARGUMENT 3 ====  NUMBER OF PARAMETRIC VARIABLES IN PARAMETRIC
    .idf FILE

# The .idf should contain the following search strings:
# sHELLsTORAGEtANKsTARTtEMPERATURE -on the line within the Hot
    Water Setpoint Temp Schedule that sets the temperature for
    the first hour of the simulation
# EnergyPlus seems to set the storage tank temperature at the
    start of the simulation to the hot water setpoint for the
    beginning of the simulation
#=======================================


args=("$@")      #Stores the arguments given by user in command
    line


# DISPLAYS INPUT VALUES BACK TO USER
echo "Energyplus parametric file name without .idf extentsion: $
    {args[0]}"
echo "Weather file name: ${args[1]}"
echo "Number of parametric runs specified in E+ file:  ${args
    [2]}"


# RUNS THE E+ PARAMETRICPREPROCESSOR GENERATING .idf FILES
parametricpreprocessor ${args[0]}".idf"


#set output of parametricpreprocessor to array and print array
    values
array=(${args[0]}*".idf")
len=${#array[*]}
echo "The array has $len members. They are:"
i=0
while [ "$i" -lt "$len" ]; do
        echo "$i: ${array[$i]}"
        let i++
done
```

```
#exit

#============ CREATING RVI FILES FOR EACH RUN AND RUNNING E+
    =====
nRuns=${args[2]}
count=1
cnt=1
rcount=2

while [ $count -le $nRuns ]; do

        #This line uses sed to replace the filename of the csv
            file within the .rvi file for each run
        sed 's/'${args[0]}'1.csv/'${args[0]}$rcount'.csv/g' ${
            args[0]}-1.rvi > ${args[0]}-$rcount.rvi


        tempTest=0
        iterCount=0

        while [ $tempTest -ne 1 ]; do
                #This line runs energyplus using the idf files
                    produced by the parametricpreprocessor
                #(E+ auxiliary program) and the weather file
                    input to this script by user
                runenergyplus ${args[0]}"-"$cnt".idf" ${args[1]}
                awkCsv=`expr $rcount - 1`
                echo "awk csv: ${args[0]}$cnt.csv"
                #Get tank temp at start and end of year
                set $( awk -F, '
                        /01\/01  01:00:00/ {
                                startTemp = $4
                                print startTemp
                                }
                        /12\/31  24:00:00/ {
                                endTemp = $4
                                print endTemp
                                }
                        END {
                                delT = endTemp-startTemp
                                print delT
                                if (delT > 0 && delT < 1.0)
                                    print 1;
                                else if (delT < 0 && delT >
                                    -1.0) print 1;
```

```
                    else print 0;
                    }' ${args[0]}$cnt".csv")
        storTempStart=$1
        storTempEnd=$2
        delT=$3
        tempTest=$4
        echo "************  Ending Temps  
            **************"
        echo "storTempStart: $storTempStart"
        echo "storTempEnd:   $storTempEnd"
        echo "delT: $delT"
        echo "tempTest: $tempTest"
        #Sets next simulation start tank temp as the end
             tank temp of the last simulation if annual
            recalc needed
        if [ $tempTest -eq 0 ]; then
        awk -F, -v VAR=$storTempEnd   '/
            sHELLsTORAGEtANKsTARTtEMPERATURE/ {
                printf("UNTIL: 1:00, %2.1f, !- 
                    sHELLsTORAGEtANKsTARTtEMPERATURE \n",
                    VAR)
                }
                !/sHELLsTORAGEtANKsTARTtEMPERATURE/ {
                print
                }' ${args[0]}"-"$cnt".idf" > awkTemp${
                    args[0]}"-"$cnt".idf"
        rm ${args[0]}"-"$cnt".idf"
        mv awkTemp${args[0]}"-"$cnt".idf" ${args[0]}"-"
            $cnt".idf"
        fi
done
#GET AND DISPLAY SF FOR RUN
set $(sf.sh ${args[0]} $cnt)
SF=$1
echo "************  Solar Fraction  **************"
echo "SF:    $SF"

let rcount++
let count++
let cnt++
#Sets next simulation start tank temp as the end tank
    temp of the last simulation
```

```
#           awk -F, -v VAR=$storTempEnd    '/
    sHELLsTORAGEtANKsTARTtEMPERATURE/ {
#                     printf(" UNTIL: 1:00, %2.1f, !-
    sHELLsTORAGEtANKsTARTtEMPERATURE \n",VAR)
#                     }
#                     !/sHELLsTORAGEtANKsTARTtEMPERATURE/ {
#                     print
#                     }' ${args[0]}"-"$cnt".idf" > awkTemp${args
    [0]}"-"$cnt".idf"
#           rm ${args[0]}"-"$cnt".idf"
#           mv awkTemp${args[0]}"-"$cnt".idf" ${args[0]}"-"$cnt".idf
    "
done

rcount=`expr $rcount - 1`
rm ${args[0]}"-"$rcount".rvi"   # DELETING EXTRA .rvi FILE THAT
    COMES OUT OF THE LOOP

#CELEBRATORY MESSSAGE
echo "Success, my friend! Now, deal with all that data."
```

B.6 ePlusTempAdj.sh

```
#!/bin/bash

#========= FILE FOR RUNNING E+ SOLAR THERMAL SIMULATION AND
    CHECK BEGINING AND END OF YEAR TANK TEMPERATURES ===
# ARGUMENT 1 ====  E+ PARAMETRIC FILENAME WITHOUT .idf EXTENSION
# ARGUMENT 2 ====  NAME OF THE WEATHER FILE WITH .epw EXTENSION
#==================================================================



args=("$@")     #Stores the arguments given by user in command
    line

        tempTest=0
        iterCount=0

        while [ $tempTest -ne 1 ]; do
                #This line runs energyplus using the idf files
                    produced by the parametricpreprocessor
                #(E+ auxiliary  program) and the weather file
                    input to this script by user
                echo "============== RUN ENERGY PLUS FILE ARG:    
                    ${args[0]}.idf"
                runenergyplus ${args[0]}".idf" ${args[1]}
                #Get tank temp at start and end of year
                set $( awk -F, '
                        /01\/01  01:00:00/ {
                                startTemp = $4
                                print startTemp
                                }
                        /12\/31  24:00:00/ {
                                endTemp = $4
                                print endTemp
                                }
                        END {
                                delT = endTemp-startTemp
                                print delT
                                if (delT > 0 && delT < 1.0)
                                    print 1;
                                else if (delT < 0 && delT >
                                    -1.0) print 1;
                                else print 0;
                                }' ${args[0]}".csv")
                storTempStart=$1
```

```
        storTempEnd=$2
        delT=$3
        tempTest=$4
        echo "storTempStart: $storTempStart"
        echo "storTempEnd:   $storTempEnd"
        echo "delT: $delT"
        echo "tempTest: $tempTest"
        #Sets next simulation start tank temp as the end
            tank temp of the last simulation if annual
           recalc needed
        if [ $tempTest -eq 0 ]; then
        awk -F, -v VAR=$storTempEnd   '/
           sHELLsTORAGEtANKsTARTtEMPERATURE/ {
                printf(" UNTIL: 1:00, %2.1f, !- 
                   sHELLsTORAGEtANKsTARTtEMPERATURE \n",
                   VAR)
                }
                !/sHELLsTORAGEtANKsTARTtEMPERATURE/ {
                print
                }' ${args[0]}".idf" > ${args[0]}".
                   idfawkTemp"
        rm ${args[0]}".idf"
        mv ${args[0]}".idfawkTemp" ${args[0]}".idf"
        fi
done
```