Evaluation of a Solar Water and Thermal Energy Storage System for Zero Energy Housing

By
Ysabel Espinal
Ismael George-Richard
Nowick
Leanne M. Sickles

Evaluation of a Solar Water and Thermal Energy Storage System for Zero Energy Housing

Submitted by:
Ysabel Espinal, Ismael George-Richard Nowick, and Leanne M. Sickles

Project Advisors:
Professor Steven Van Dessel, Director of Architectural Engineering
Professor Ali Fallahi, Assistant Teaching Professor

Abstract

Residences account for 21% of the total energy demand in the United States, one-third of which is due to heating, ventilation, and air conditioning (HVAC) systems. As such, there is great potential to reduce the consumption of HVAC systems thus decreasing the home's overall energy demand. The company Unity Homes is working to address this concern by selling energy efficient homes to the general public. In collaboration with Unity Homes, we sought to re-innovate the design of a solar water and thermal energy storage (TES) system to be used within one of their homes. We recommend further investigation into the feasibility of the integration of our system as well as the potential for use as a cooling and domestic hot water system.

Acknowledgements

We would like to thank our advisors, **Professor Van Dessel** and **Professor Ali Fallahi** for guiding us through our research and system implementation. Both their ideas, support, and interests encouraged us to move forward throughout the academic year.

We would also like to express our gratitude to our project advisor and sponsor, **Ed Curtis**, for providing the funds and necessary information to complete the construction of our system.

Additionally, we would like to thank **Russell Lang**, Lab Manager of the Civil & Environmental Engineering Department at WPI, for aiding the group throughout the construction of the system and offering his support and guidance. This project would have not been done without you.

Finally, we would like to extend our sincere thanks to following individuals, departments, institutions, and organizations for supporting us throughout the completion of this major qualifying project:

- **Andrew Dey**, Operations Director of Unity Homes, for giving us the opportunity to visit and evaluate their house platforms.
- **Professor Kenneth M. Elovitz**, Adjunct Teaching Professor at Worcester Polytechnic Institute, for helping us with the mechanical components of our project.
- **Ted McCarty and his crew**, Lead Electrician at WPI, for offering their skills and knowledge in wiring the trailer, and
- **Professors James O’Rourke and Stephen Bitar** of the Electrical and Computer Engineering Department at WPI, for offering their time and knowledge on the control schematics for our system.

Table of Contents

Authorship

	Primary Author	Secondary Author	Editor
Introduction	YE	--	LS
Background			
History of Heating New England Homes	LS	--	LS
Net Zero Energy Design for Homes	LS	--	LS
Passive Methods for Zero Energy Design	IN	LS	LS
Optimizing Building Envelopes	IN	LS	LS
Orientation and Effective Site Planning	IN	LS	LS
Passive Designs	IN	LS	LS
Active Methods for Zero Energy Design Systems within Homes	YE	--	LS
Solar Water Heater Systems	YE	--	LS
Geothermal Heat Transferring Systems	YE	--	LS
Electrical Systems	YE	--	LS
Unity Homes	LS	--	LS
Design	LS	--	LS
Construction Process	LS	--	LS
Materials	LS	--	LS
Mechanical Systems	LS	--	LS
Passive House Standard	LS	--	LS
Problem Statement and Objectives	LS	--	LS
Experimental Set Up and System Functionality			
Experimental Set Up	YE	LS	LS
System Functionality	YE	LS	LS
Methodology			
Objective 1	LS	IN	LS
Objective 2	LS	--	LS
Site Selection	YE	LS	LS
Establishing a Peak Heating Load Profile	YE	--	LS
Materials, Equipment and Sizing	YE	LS	LS
Creating a Mathematical Model	YE	LS	LS
System Design	LS	--	LS
System Construction	LS	--	LS
Electrical Design and Controls	YE	--	LS
Objective 3	IN	LS	LS
Objective 4	LS	--	LS
Results			

Objective 1	IN	--	LS
Objective 2	YE	LS	LS
Establishing a Peak Heating Load Profile	YE	--	LS
Equipment Sizing	YE	--	LS
Creating a Mathematical Model	LS	--	LS
System Design and Construction	LS	--	LS
Electrical Design and Controls	YE	--	LS
Objective 3	LS	--	LS
Objective 4	LS	--	LS
Conclusion	LS	--	LS

List of Figures

List of Tables

Executive Summary

Introduction

In the United States, buildings account for 38% of all carbon dioxide emissions, they consume 13.6% of all potable water (15 trillion gal./year), and use 73% of the total electricity consumption ("This is LEED: Better Buildings are out Legacy," n.d.). In 2007, an annual energy review performed by the U.S. Energy Information Administration (EIA) revealed that residences account for 21% of the total energy demand in the United States (Meyers, 2010). Furthermore, a 2009 Building Energy Database concluded that heating, ventilation, and air conditioning (HVAC) systems account for one-third of a building's energy consumption (Noonan et al., 2013). The company Unity Homes is working to address this issue by selling energy efficient homes to the general public. In collaboration with Unity Homes, we sought to re-innovate the design of a solar water and thermal energy storage (TES) system to be used within a New England Home.

Background

Our project focuses on designing a solar water heating and thermal energy storage (TES) system to minimize energy usage within single-family homes. To better understand the need for such a system and determine how it can be optimized for a single-family home we conducted research that focused on the optimization of a home through passive methods using the successful design of the homes built by Unity Homes as an example. We first discuss the different methods for heating and cooling homes that have been used and which lead to the most recent stride of building optimization and energy efficiency: net zero energy. Achieving a net zero energy design requires the building to be optimized both passively and actively, we examine methods used to meet these standards. Lastly, we discuss the design and building process of the net zero energy homes produced by Unity Homes as their homes are the platform for our solar water heating system.

Process

In collaboration with Unity Homes, we sought to improve their home design by investigating both passive and active changes to their design. In order to complete this goal we completed the following tasks:

1. *Improve the design of a Unity Home using passive methods through simulation using energy modeling software*

2. *Design, build, and test an innovative heating system to heat a small space during the winter season*
3. *Determine the feasibility for our innovative heating system to be used within a Unity home*
4. *Develop a set of strategies and recommendations for ways to further our research and improve Unity Home's house design both passively and actively*

Recommendations

Passive Changes for Unity Homes

We recommend that Unity Homes continues to use their current design and construction methods. Based on our energy modeling we found that the current window type, insulation, and orientation of Unity Home's houses provides the most efficient and cost effective solution.

Future Work on Solar Water Heating System

We recommend that a future project be developed to further extend and integrate a controls set up for our system. The control schematic, pump schedule, and pump control flow chart that we created should help guide future work as they collectively describe how our system is intended to operate. In addition to the automatic control of the pumps and motorized valve, the temperature sensors attached along the piping and the sides of the drums of the heating loop should be connected to the RESOL controller, or an alternative source, in order to automatically collect temperature at specified time intervals. A proper controls set-up to accomplish these two tasks will allow our system to function seamlessly and without manual operation.

We recommend that a future project be developed to continue our work on creating an operable system. Further investigation is needed to determine why the solar loop is not able to maintain pressure. Once a conclusion is reached and the necessary steps are taken to solve the problem, filling of the heating loop can commence. Successful filling of both loops will allow the system to be turned on and data collection can begin.

We recommend that a future project be developed to modify our system to allow for space cooling and domestic hot water use. The marine heat pump that we purchased has the ability to operate in cooling mode. Modifying our system to include space cooling would increase its usefulness as it would be able to function as a modern HVAC system currently does. When conducting research for building our system we found that similar systems to ours had been developed to provide hot water to homes. Thus, we believe that the integration of domestic hot water into our system is possible and we believe that a final version of our system that includes heating, cooling and domestic hot water is a system that Unity Homes is looking to integrate into their homes.

Unity Homes Integration

We recommend that further investigation be made to obtain a system efficiency value. In order to successfully integrate our system model into the Xyla platform and overall efficiency value needs to be calculated. This calculation can only be made once results are obtained from either a mathematical model or experimental testing. If a model will be used, further work to develop the mathematical model that we presented in this paper is necessary to accurately represent our system. Alternatively, a new model could be used or newly developed to satisfy our system parameters.

We recommend that serious consideration be taken to determine the feasibly of integrating our system into a Unity Homes house. Because our system requires a large amount of space, thought needs to be given as to where the system will be located. Depending on the number of solar collectors and storage drums necessary the drums may be able to be located inside the home, possibly in the basement. Additionally, thought must be given to the appearance of the system and whether or not a roof mounted solar collector will be favorable over a ground mounted system.

We recommend that a cost analysis be performed to compare our systems costs with the cost of the HVAC system already used within a Unity Home. Taking into account both the initial cost of the system as well as the cost savings allowed by the elimination of electric or gas consumption a cost analysis can be performed. This analysis will further illustrate the feasibility of the integration of our system. Additionally, calculations and an associated cost analysis can be performed for our system with the addition of using solar panels as a means to power our system. This addition to our system would not only provide potential long term cost savings, it would also create an HVAC system to help in achieving a net zero energy house design.

Conclusions

The goal of our project was to improve Unity Home's home design by investigating both passive and active methods. We conducted research, performed energy modeling analyses, and built a solar water heating system to formulate recommendations for Unity Homes and future WPI students. Our research assisted us in choosing variables to consider when attempting to passively improve Unity Home’s design. The energy modeling that we performed to accomplish this allowed us to conclude that Unity Home’s current design and construction techniques are the most efficient and cost effective. When considering active improvements we were able to conclude that our system would need to include an additional solar collector in order to effectively heat either the trailer or the Xyla house. We were also able to formulate many recommendations to assist future WPI project teams that continue our work as they outline our intentions for successfully completing of our work as well as additional topics to investigate upon obtaining further results.

1.0 Introduction

In the United States, buildings account for 38% of all carbon dioxide emissions, they consume 13.6% of all potable water (15 trillion gal./year), and use 73% of the total electricity consumption ("This is LEED: Better Buildings are our Legacy," n.d.). In 2007, an annual energy review performed by the U.S. Energy Information Administration (EIA) revealed that residences account for 21% of the total energy demand in the United States (Meyers, 2010). Furthermore, a 2009 Building Energy Database concluded that heating, ventilation, and air conditioning (HVAC) systems account for one-third of a building's energy consumption (Noonan et al., 2013). Unlike commercial buildings, residences are more likely to waste energy due to the inefficient tendencies of homeowners. As they are in direct control of the temperature and operation settings, homeowners are more likely to set and maintain a higher temperature during the winter and a lower temperature during the summer throughout the day with no regard to occupancy status. In order to decrease energy consumption, technological advances must be made to control the energy usage within residences (Meyers, 2010).

In an effort to reduce energy consumption in homes, the idea of "Net Zero Energy Design" has been introduced. A home is considered to be net zero if the annual energy consumption of the building is approximately equal to the amount of renewable energy generated on site. Homeowners have been exposed to the use of solar energy such as the use of photovoltaics, and flat or evacuated tube collectors to both generate electricity and meet heating and/or cooling needs. In conjunction, many scholars have initiated studies to explore the use of solar collectors as a means to provide space heating for homes. A recent study conducted by Engineers from the Indian Institute of Technology, explored the use of a mathematical model to determine the design space synthesis and optimization of solar water heating systems. The design was based on a typical layout consisting of a solar collector array and an insulated storage tank. It was observed that there was a maximum and minimum storage volume for a given solar fraction and collector area and a maximum and minimum collector area for a given solar fraction and storage volume (Kulkami, 2006). Their proposed data can be adopted and modified to fit other project components and needs.

The company Unity Homes is working to address this concern by selling energy efficient homes to the general public. In collaboration with Unity Homes, we sought to re-innovate the design of a solar water thermal energy storage system to be used within one of their homes. After meeting with the Operations Director of Unity Homes and performing preliminary research, it was evident that the main area of improvement for their homes is the HVAC system. To accomplish our goals of this project we carried out the following tasks: First, we aimed to improve the design of a Unity Home using passive methods through simulation using energy modeling software. Second, we designed, built, and tested an innovative heating system to heat a small space during the winter season. Third, we determined the feasibility for our innovative heating system to be used in a Unity home. Lastly, we developed strategies and recommendations for ways to further our research and improve Unity Home's house design both passively and actively. By accomplishing these tasks, we were able to provide Unity Homes with potential strategies to improve the HVAC system in their designs, and set a research platform for future Worcester Polytechnic Institute students.

2.0 Background

Our project focuses on designing a solar water heating and thermal energy storage (TES) system to minimize energy usage within single-family homes. To better understand the need for such a system and determine how it can be optimized for a single-family home we conducted research that focused on the optimization of a home through passive methods using the successful design of the homes built by Unity Homes as an example. We first discuss the different methods for heating and cooling homes that have been used and which lead to the most recent stride of building optimization and energy efficiency: net zero energy. Achieving a net zero energy design requires the building to be optimized both passively and actively, we examine methods used to meet these standards. Lastly, we discuss the design and building process of the net zero energy homes produced by Unity Homes as their homes are the platform for our solar water heating system.

2.1 History of Heating New England Homes

As home heating stems from the need for thermal comfort, the first heating ventilation and air conditioning (HVAC) system was introduced in the early 1900's. It was not until later in the century that there was a push towards energy efficiency, where the design and production of HVAC systems began to focus on reducing energy consumption. In addition to improving the traditional HVAC systems, newer systems that incorporate renewable resources have also been introduced to the market. Among the most common newer HVAC system is solar heating as it is a cost effective and pollution reducing system. As this system, and even newer systems are being developed, new ideas, such as net zero energy, are being explored to increase efficiency and reduce energy consumption.

2.2 Net Zero Energy Design for Homes

A building is considered to be net zero if it can generate as much energy through the use of renewable resources as the building consumes. The concept of a net zero energy building was most recently introduced in the Energy Independence and Security Act of 2007 where an initiative was set forth to "...develop and disseminate technologies, practices, and policies for the development and establishment of zero net energy commercial buildings…" (Congress, 2007). As this initiative aims to achieve net zero energy in 50% of all commercial buildings by 2050, there is no mention of residential buildings. Because residential buildings also play a major role in annual energy consumption, the National Institute of Standards and Technology (NIST) hosted a workshop to educate the residential building stakeholder community on achieving net zero energy (NZE) in new and existing homes.

The workshop focused on gauging participants perspectives on the following questions:

- “What are the key characteristics of future NZE homes and the residential building community?
- What are the challenges and barriers that impede the design, construction, and purchasing of NZE homes?
- What are the potential concepts that could be included in a future guidance document for the residential building community to aid in the design and construction of NZE homes?” (McNabb, 2013).

Each question was addressed within each of the three sections of the workshop where each section’s collaboration resulted in a comprehensive list ranging from low to high priority items for the design and operation of a net zero energy home. Additionally, a list of challenges and corresponding “future guidance document” to overcome each of the challenges is described. As a result, the workshop developed fundamental concepts that are being further developed today as companies strive to make net zero homes a reality.

The three sections of the workshop focused on key design aspects of net zero energy homes, key technology and equipment aspects of future net zero energy homes, and the human element of net zero energy homes. From the sections a compiled list can be formulated to identify high, medium and low priority items that need to be incorporated into a net zero home, some of which are listed below:

“High:

- modest footprint with minimal carbon footprint
- integrated heating, cooling, ventilation and dehumidification system that is properly sized to optimize the building performance
- use of high efficiency, affordable HVAC systems
- quality construction that incorporates techniques to achieve a tight, well insulated envelope
- simple systems that are easy to use and maintain
- real time energy metering

- maximize the benefits of daylighting
- the use of automation and advanced controls to minimize electricity use for plug loads
- designed so that the owner can easily operate the home energy efficiently

Medium:

- use of triple pane windows
- use of properly sized, on-site renewable energy to generate power and heat

Low:

- energy load served by a variety of methods
- ventilation that is both natural and mechanical
- water used efficiently and conserved
- provide feedback to occupants on energy management performance through monitoring and display systems" (McNabb, 2013).

As the participants created the lists they also noted some foreseen challenges with this list of design and owner operation elements such as being able to "evaluate and compare energy performance and the selection of effective technology, building materials, methods of construction, and siting options" (McNabb, 2013). Because homeowners may not be educated as to how changing behavior and energy use can improve energy performance or on how purchasing a home based on maintenance costs rather than initial purchase cost can save them money while reducing their carbon footprint, net zero energy homes may not be widely purchased or built. Thus a "guidance element" was identified to solve this problem; the participants suggested that a home scoring system be developed to compare the performance of net zero homes to other homes for sale. With regards to the selection of effective technology, building materials, methods of construction, and siting options it has been observed that the mechanical systems in buildings, especially low load homes, are often sized incorrectly and it was determined that the best way to address this is to wait for new technologies to be developed that are high efficiency and affordable (McNabb, 2013).

Although a standard for net zero energy residential buildings is still yet to be officially established, the International Living Future Institute offers a Net Zero Energy Building Certification. This certification is one of three certifications under the Institute's Living Building Challenge which "is an attempt to dramatically raise the bar from a paradigm of doing less harm to one in which we view our role as a steward and co-creator of a true Living Future" (International Living Future Institute, 2017). The Challenge defines twenty imperatives that must be achieved to meet the Challenge, four of which must be met to obtain the Net Zero Energy Building Certification: Limits to Growth, Net Positive Energy, Beauty + Spirit and Inspiration + Education. The Limits to Growth imperative limits a project to only being built on greyfields or brownfields and requires that no petrochemical fertilizers or pesticides be used for the operation and maintenance of on-site landscaping. The Net Positive Energy imperative can only be met if one hundred percent of the project's energy needs is supplied by on-site renewable energy on a net annual basis without the use of on-site combustion. The Beauty + Spirit imperative relates to the project's integration of public art and design features intended for human delight. Finally, the Inspiration + Education imperative requires that educational materials about the operation and performance of the project be provided to the public in addition to hosting an annual "open day" for the public in order to motivate others to make meaningful changes in their lives (International Living Future Institute, 2017).

Since the initial concept of a net zero energy home was established, new strategies and technologies have been developed and integrated into residential buildings that address many of the items on the list created by NIST in 2011. These strategies and technologies can be easily categorized as being either a passive or active system where different combinations of these systems have been used to advance the design and construction of homes that make net zero energy homes a seemingly achievable goal for the future.

2.3 Passive Methods for Zero Energy Design

In order to produce a zero energy design both passive and active methods can be considered. Because a net zero design is achieved when the amount of energy consumed is equal to the amount of energy produced it is most commonly thought that active systems, such as photovoltaic cells, are the only way to attain a net zero energy design. Although these active systems play a major role in net zero energy design, passive systems, such as the building's envelope and orientation, contribute greatly to the performance of a home and thus increases the efficiency of the active systems.

2.3.1 Optimizing Building Envelopes

The building envelope is a large contributing factor to achieve a zero energy design as it accounts for a large portion of the building's heat loss in the winter and heat gain in the summer. A building's envelope consists of all of the walls, windows and doors, the roof and the ground floor. For the walls, roof and floor, the heat gain and heat loss is mainly controlled by the insulation.

Insulation works by slowing the conductive heat flow, where different insulation materials provide a greater resistance to conductive heat flow. This resistance is measured based on the material's thermal resistance, its thickness and its density and is expressed as what is known as a material's R-value. Depending on where the building is located different R-values are recommended; larger R-value insulation has a greater insulating effectiveness and is thus recommended in colder climates whereas in warmer climates lower R-value insulation is recommended. It is also important to understand that the material R-value will not be the actual R-value of the wall, roof or floor due to what is known as thermal bridging. This occurs because heat is able to flow through studs and joists as they provide a break in the insulation and allow for a conductive flow through the envelope. Different types of insulation have different R-values and are more effective at reducing conductive flow. The most commonly used insulation is a fiberglass batt insulation due to its lower cost and ability to fit into any space. Although these benefits are appealing, in order to achieve a large R-value the thickness of the insulation must also be large as typical batts have R-values that range from R-2.9 to R-4.3 per inch. Another type of insulation that is commonly used is foam board insulation which has R-values that range from R-4 to R-6.5 per inch of thickness. In addition to having a larger R-value per thickness than most insulations, foam boards are able to reduce heat conduction through structural elements. Another type of insulation that is becoming increasingly more common is sprayed-foam insulation. Although this type of insulation costs more than other types of commonly used insulations, sprayed-foam insulation has R-values that range from R-3.7 to R-6.2 per inch and practically eliminates air leakage as it expands to completely fill any space. Because of this, sprayed-foam insulation has been known to reduce other costs associated with weatherizing a home which makes up for the larger initial cost of the product (Types of Insulation, n.d.).

Another element of the building envelope that contributes to the building's heat loss and heat gain are the windows. Similar to how studs and joists break up the continuous flow of insulation in the walls, the windows also act as a break in the structure where the envelope is susceptible to air leakage. Additionally, windows have their own efficiency factor known as the U-value which is determined by both the material of the window frame and the glazing type where the lower the U-value, the more energy efficient the window is. Window frames can be made from metal, fiberglass, vinyl or wood materials which each have their own advantages and disadvantages. In terms of thermal resistance, the most effective frames are those made of fiberglass or vinyl as both types have air cavities that can be filled with insulation to increase their thermal performance. The window glazing contributes greatly to the overall window efficiency; they are many different types of glazing including insulated and low-emissivity. An insulated window glazing has two or more panes of glass that are spaced apart leaving an insulating air space which lowers the U-value of the window. Alternatively, a low-emissivity, or low-e, coating on a window glazing controls heat transfer which reduces energy loss by 30 to 50 percent (Window Types, n.d.).

As the performance of a building is largely controlled by the building's envelope, ensuring that the conductive heat flow and the air leakage through all of the enclosure elements is minimized is of great importance. In order to determine the effectiveness of these elements, different tests can be performed such as a blower door test or thermal imaging. These tests identify areas within the building where air leakage is occurring and report a value measured in air changes per hour (ACH), where .6 ACH would qualify a building as efficient.

2.3.2 Orientation and Effective Site Planning

In addition to optimizing the building's envelope, taking the building's orientation into account is important to achieve an effective passive design. When considering the orientation of the building both the sun's position and the climate zone play a major role. For the northern hemisphere, south facing windows allow the most sunlight in year-round, north facing windows admit even lighting with almost no summer heat gain, and east and west facing windows provide daylight in the morning and evening respectively but admit a lot of heat in the summer. With these facts in mind, careful analysis should be conducted for a particular site to obtain the optimum orientation, where the ideal orientation would be the one to allow sunlight to penetrate the building when it is needed and passively heat the whole house, as well as provide daylighting to the majority of the interior spaces (Daylighting, n.d.).

2.3.3 Passive Designs

Using the concepts that have been developed and understood about a building's envelope and orientation, different techniques and designs have been developed to optimize a building. These designs, discussed below, can be utilized for many applications within a building, but ultimately work to optimize a building passively.

2.3.3a Thermal Energy Storage Methods and Systems

Adequate thermal energy storage (TES) methods and systems in buildings have growing potential in energy conservation. TES can overcome the lack of thermal energy supplied through an HVAC system and produce the energy that is demanded by the space. By applying TES in the form of active and passive systems, wasted heat can be used, peak loads can be shifted, and an overall more rational use of energy can be achieved. Buildings that incorporate TES have the potential to be more reliable and efficient, less costly to operate, and more environmentally friendly as it produces less CO2 emissions.

TES systems and methods have been classified as either passive or active systems. Passive systems work to optimize the use of *"…naturally available heat energy sources in order to maintain the comfortable conditions in buildings and minimize the use of mechanically assisted heating or cooling systems"* (de Gracia L.F. Cabeza, 2015). Some passive systems and methods include: Thermal mass, orientation/solar heating, shading, ventilated facades, phase change materials, coated glazing, and free cooling (night ventilation) techniques. On the contrary, active systems provide a large factor of control over the indoor conditions as they are mechanically assisted. Active systems shift the "thermal load from on-peak to off-peak conditions in several applications, such as domestic hot water, or heating, ventilation, and air-conditioning (HVAC) systems" (de Gracia L.F. Cabeza, 2015).

There are three methods of thermal storage: Sensible, latent, and thermochemical energy storage (see Figure 1).

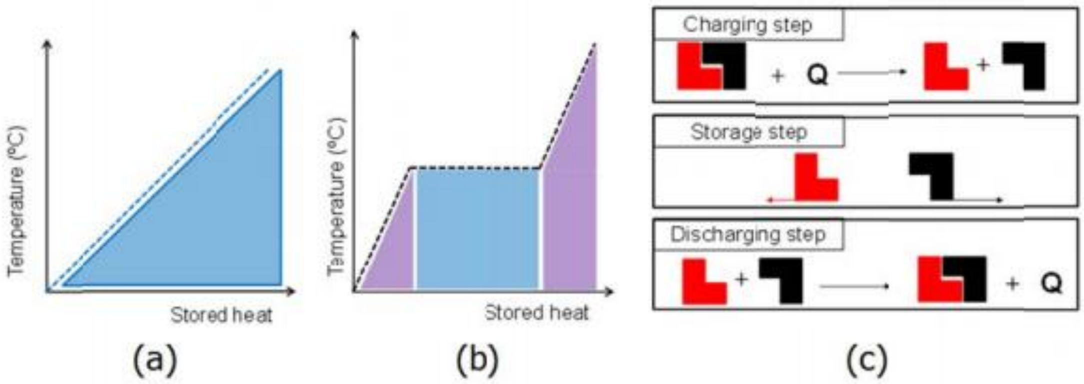


Figure 1: Thermal Energy Storage Methods: (a) Sensible, (b) Latent, and (c) Thermochemical Recations

(de Gracia L.F. Cabeza, 2015)

Sensible heat storage is the simplest method to store thermal energy; it is facilitated by applying a temperature gradient to a media (either liquid or solid) in order to absorb or release heat. Water is the most commonly used sensible thermal storage material, although ceramic materials (concrete, cement, etc.), some natural stones like marble, granite, clay, sandstone, and polymers such as PUR, PS, and PVC are also used. Sensible heat storage is cost effective and avoids risks from toxic materials. Often, sensible storage materials are part of the buildings structure and therefore do not require extra space. However, sensible heat storage often requires a large volume of material depending on the amount of desired heat energy to be stored (de Gracia L.F. Cabeza, 2015).

On the other hand, latent storage has a higher storage density and therefore requires less volume of material as represented in Figure 1 (b). Latent heat storage is captured through phase change materials (PCM) which make use of the latent heat between phase changes. The process of changing phases (solid to liquid, and reverse) in a substance either stores or releases a large amount of energy as heat. Some materials that work well as PCM materials include paraffin, fatty acids, and salt hydrates. Each material has specific phase change properties, such as temperature and conductivity so each PCM is only advantageous in its own designed application based on its physical properties (de Gracia L.F. Cabeza, 2015).

The last kind of material used in TES systems is thermochemical (Figure 1 (c)). This process, though potentially very efficient, is under development and currently has no present applications in the building sector. These materials store and release heat via reversible endothermic and exothermic reactions. As seen in the schematic, a thermochemical object is charged and then splits into objects B and C. These separate pieces can be stored until the energy is desired to be released/discharged (de Gracia L.F. Cabeza, 2015).

2.3.3b Trombe Wall

Named after Felix Trombe, who, in the late 1950's, had engineered a simple yet effective passive design that is still used today, a trombe wall is built on the equator-facing side of a house where it can maximize solar gains (a northern hemisphere house would have a trombe wall facing south; southern hemisphere, facing north).

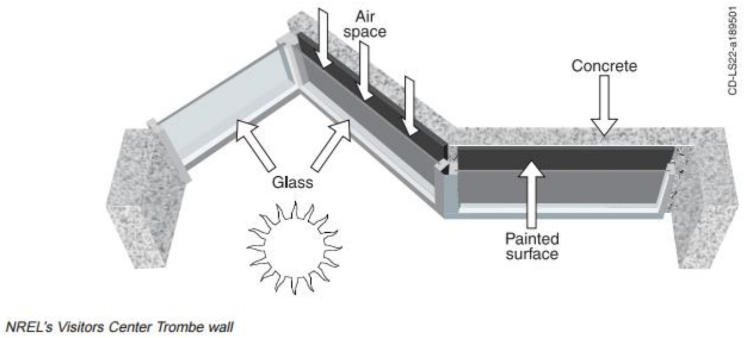


Figure 2: Trombe Wall at NREL's Visitor Center

(NREL, n.d.)

Trombe Walls incorporate a window, an air space and then a thick layer of thermal mass right behind the window which helps trap solar gains during the day so that more heat will be absorbed. The air temperature in the air gap will rise to become very high during the day therefore forcing the heat to flow deeper into the wall since the temperature gradient across the thermal mass layer from the air gap to the living space conditions will be very large.

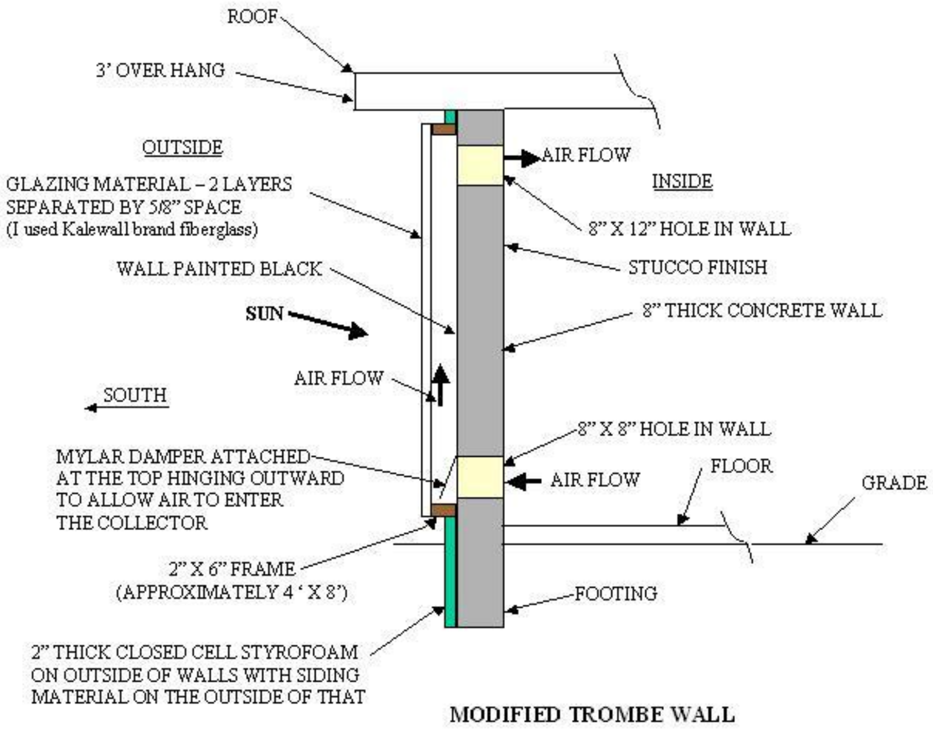


Figure 3: Northern Hemisphere Trombe Wall Schematic

(NREL, n.d.)

A passive air flow will occur within the wall naturally with a high wall vent and a low wall vent, as seen in Figure 3. As air is heated within the air gap it will rise and create a natural convective flow that will suck in cooler air from the living space and expel it back into the space as warmer air while the excess heat will be absorbed into the wall. During the night the thermal mass layer will slowly release its stored solar heat from the day's sunlight into the living space (NREL, n.d.).

Proper shading and reflective glazing can optimize this design so that there is no heating effect in the summer, when it is desirable to cool the space. In the summer, when the sun is higher in the sky, an overhang can block the sunlight from warming the wall and the use of reflective glazing in the windows can make the sunlight bounce off the window to eliminate heat gain (NREL, n.d.).

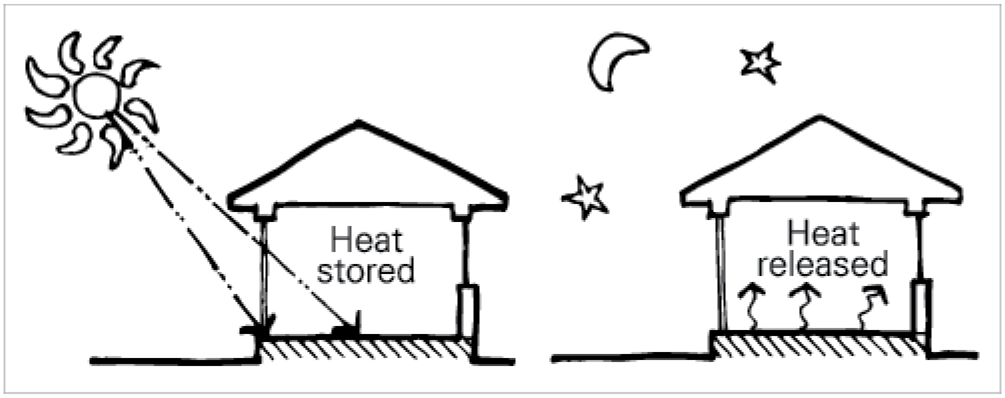
2.3.3c Water Wall

Water is twice as effective at storing thermal energy as concrete, and 4800 times better than air. The thermal energy stored in the Earth's oceans work as a giant thermal battery to keep temperature ranges on the planet within the optimal range. A water wall is a wall made of large tanks of water placed behind an area of windows facing the equator-direction (south for northern hemisphere buildings, north for southern hemisphere buildings) where the water is able to absorb and store heat collected from the sun. The heated water can then be used to circulate the air within a home by forcing air from the living space through the water in the tanks and then back into the living space. Alternatively, the home could be heated by using a fan to blow over the exterior of the tanks to disseminate the heat from the tanks into the home (Bainbridge, 2005).

2.3.3d Basic Passive Solar with Thermal Mass

A more common passive system that is used within homes is thermal mass through use of typical home construction and features. Materials that have high thermal mass, such as concrete, brick and tile, have the ability to absorb and store heat. The heat is absorbed into the material throughout the day as the sun shines on it and then it is released at night when the outdoor temperature drops.

For New England homes, having a large amount of south facing glazing that allows light to shine onto the thermal mass within the home such as a concrete floor or a brick chimney is ideal. This allows for the most heat to be absorbed during the day that can then be released during the night. In the winter, the stored heat is released directly into the home and in the summer, the stored heat that is released into the home can be drawn out by the cool night breezes seen in Figure 4. Although thermal mass can be an effective way to reduce energy costs while



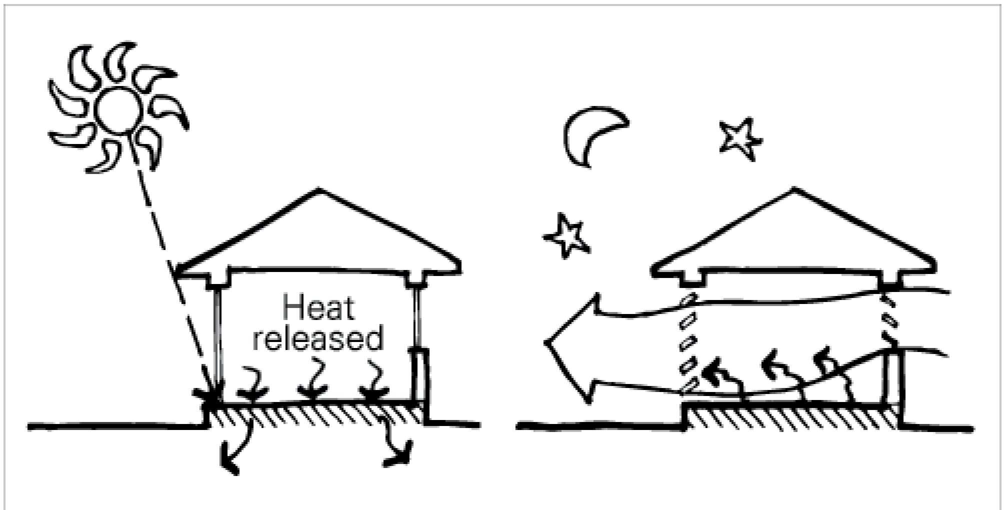


Figure 4: Thermal Mass in the Winter (Top) and Thermal Mass in the Summer (Bottom)

(Reardon, n.d.)

increasing comfort, poor use of thermal mass can have an opposite effect. Making sure that glazing is facing the appropriate direction and the right amount of shading, ventilation, insulation and thermal mass is used is crucial to an effective thermal mass system (Reardon, n.d.).

2.4 Active Methods for Zero Energy Design Systems within Homes

To create an optimal home design it is best to integrate passive systems before introducing active systems; this is because passive systems create natural, free energy. Although a completely passive design would be optimal, it is difficult to obtain sufficient control and meet demand. As a result, active systems are introduced into the design where an active system is defined as “a solar heating and/or cooling system that requires external mechanical power to move the collected heat” ("Active System," n.d.). These systems include mechanical and electrical components, both working simultaneously. In small applications, such as households, the collaboration of mechanical and electrical systems are key in designing an energy efficient home.

2.4.1 Solar Water Heater Systems

2.4.1a Solar Collectors

In active solar systems, solar collectors are one of the most important components. These devices are designed to meet specific temperature requirements and climate conditions for various applications. Solar collectors absorb the sun’s light energy and then convert it to thermal energy. The thermal energy can then be used for various operations, such as heating water or providing space heating or cooling ("Active Solar Systems," n.d.). There are various types of solar collectors on the market, but the most common are flat-plate and evacuated tube collectors.

Flat-plate collectors are the most common solar thermal systems for water and space heating. The typical configuration of a flat-plate collector looks very similar to an oversized skylight; the casing is typically made out of an insulated metal box with a glass or plastic cover, with a dark-colored absorber plate ("Active Solar Systems," n.d.). As seen in Figure 5, a glazed system consists of an absorber plate, insulation, flow tubes, and a header. This glazing can be made out of transparent or translucent material that allows light to strike the absorber plate. Having a dark absorber plate is essential in the design of the system, as a darker plate absorbs more light thus creating more thermal energy ("Active Solar Systems," n.d.).

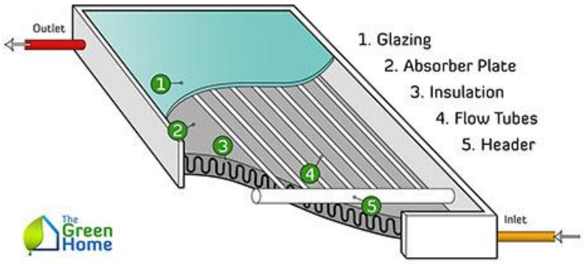


Figure 5: Glazed Flat Plate Solar Collector

(Jones, 2013)

When the light passes through the glazing and hits the absorber, the absorber will start to heat up, converting the solar radiation into thermal energy. This thermal energy is then transferred to the air, as an air flat-plate collector system, or the water, as a liquid flat-plate collector system as it travels through the collector after entering through the yellow inlet tube seen in Figure 5. An air flat plate collector is primarily used for space heating. Air enters the system through natural or forced convection; in natural convection, air simply flows into the device, whereas in forced convection, air is deliberately supplied to the device either by a fan or pump.

In lower-temperature applications, such as swimming pool and spa heaters, unglazed systems are typically used. Unglazed solar collectors are typically referred to as liquid flat-plate collector systems. As seen in Figure 6, unglazed systems typically consist of a specified number of smooth or ribbed ¼” tubes running the length of the device. The tubes can be either laid out parallel to each other or connected in one continuous tube. When light strikes the straight risers, the water coming into the lower manifold heats as it rises up the tubes. This heated water is then fed into the upper manifold and delivered to its source ("Solar Pool Heating," n.d.).

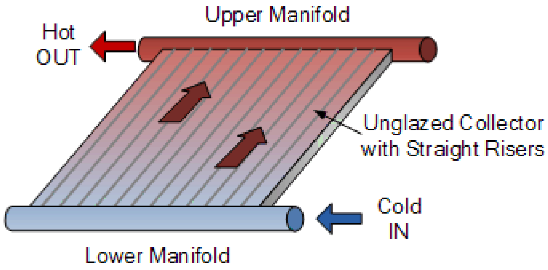


Figure 6: Unglazed Flat Plate Solar Collector

("Solar Pool Heating," n.d.)

In pool applications, unglazed systems heat the water to the surrounding air temperature, thus resulting in little to no heat loss. Because it is able to eliminate heat loss, this system is considered more efficient than glazed systems. Since this system is highly dependent on the ambient temperature surrounding the pool, unglazed solar collectors should only be used if the surrounding temperature is greater than the temperature in the water ("Solar Pool Heating," n.d.).

High temperature evacuated tube collectors typically function at a higher efficiency than flat-plate collectors due to the structure and mechanism of the system. Seen in Figure 7, the collector consists of an array of vertical, parallel, evacuated tubes which connect to a horizontal manifold. Examining the cross section of the tube reveals that the components are made out of an outer and inner glass. Inside the glass is a copper pipe, which carries out the cycle of heating and cooling the water ("Solar Geyser Technology Explained," n.d.).

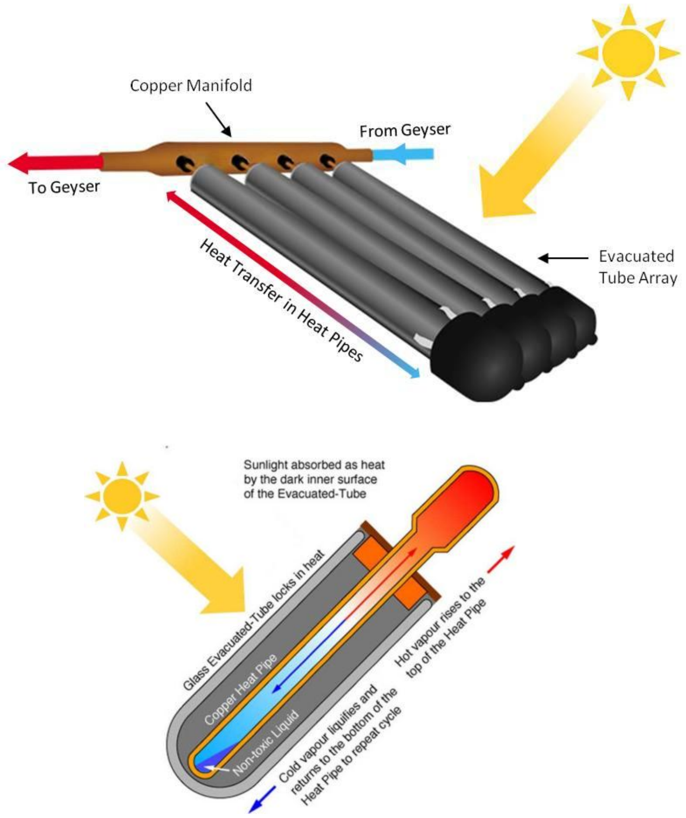


Figure 7: Evacuated Tube Array and Cross-Section

("Solar Geyser Technology Explained," n.d.)

In combination with the evacuated tubes dark inner surface, the glass acts as a vacuum by locking in the solar radiation from the sun. When sunlight enters the outer glass tube and strikes the absorber, the solar radiation is converted into thermal heat. This heat then warms the water entering the copper tube, causing the water to flow out of the tube towards the upper manifold.

In order to create a vacuum within the glass tubes the air is “evacuated,” or removed from either side of the copper tube during the tube’s production. By doing so, it ensures minimal conductive and convective heat losses throughout the structure. Even though the collector acts as a vacuum, during conductive heat transfer, the water will move from a warmer to colder surface. However, the amount of heat lost during this process is miniscule compared to amount of heat transferred to the water in the absorber tube ("Active Solar Systems," n.d.).

Unlike flat-plate collectors, evacuated tube collectors can be used in cold, cloudy climate and hot, high temperature climates as they can withstand up to 350°F. Additionally, the round shape of the tube allows for more direct sunlight throughout the day whereas the fixed position of the flat-plate collectors only allow for direct sunlight at noon. Due to the technological advances present in evacuated tube collectors, they tend to be more expensive than flat-plate collectors ("Active Solar Systems," n.d.).

2.4.1b Variance in Evacuated Tube Collectors

Evacuated tube collectors come in two main configurations: direct flow and heat pipe. In a direct flow evacuated tube, also known as “U” pipe collectors, the pipe within the tube is bent into a “U” shape where cold water flows into one end and is heated before it exits the other end, this can be seen in Figure 8.

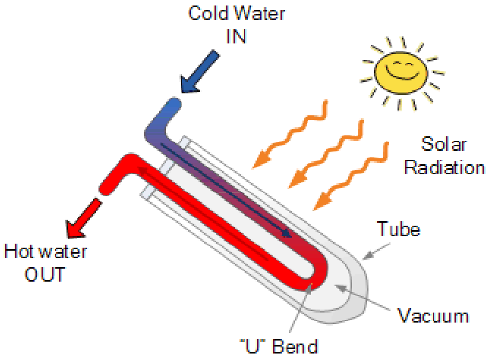


Figure 8: Direct Flow Evacuated Tube Collector

("Evacuated Tube Collector," 2017)

Since there is a direct flow of fluid through the heat pipe, the component does not exhibit a heat exchange between fluids. For this reason, many solar industry professionals believe direct flow evacuated tube collectors are the most efficient out of the two main collector configurations.

Unlike a direct flow system, a heat pipe evacuated tube consists of a single, straight line copper pipe sealed within a vacuum tube. Seen in Figure 9, the heat pipe is depicted as a “heat pipe evaporator” which runs continuously into the heat pipe condenser that is located within the upper manifold (Jafarkazemi, 2012).

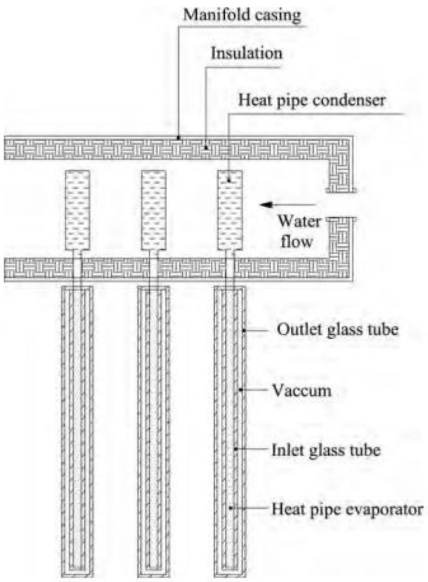


Figure 9: Heat Pipe Evacuated Tube Schematic

(Jafarkazemi, 2012)

In practice, the heat pipe usually contains a small amount of alcohol/water and some other additives to prevent corrosion or oxidation. When sunlight hits the surface of the collector, the liquid inside the heat pipe turns into hot vapor due to its vacuum enclosure. As the vapor accumulates, the gas rises to the top condenser and heats the fluid passing through the upper manifold. Once the vapor losses energy and cools, it condenses back to a liquid and flows back down the pipe; this process repeats throughout the day as the alcohol/water mixture inside the heat pipe is heated and cooled (Measuring Solar Thermal Energy, 2012).

2.4.1c Open-Loop and Closed-Loop Active Systems

There are two main types of active solar water heater systems, an open-loop (direct system) and closed-loop (indirect system). An open loop system is optimal for warm climates as it utilizes pumps to distribute water directly from the household through solar collectors where it is heated and then returned to the house for use or stored for later use in storage tanks. This system cannot be used in colder climates due to the potential for freezing during the winter months. To account for this, a closed loop system is used; the system pumps heat transfer fluids, such as glycol or a water/antifreeze mix, through the solar collectors and utilizes heat exchangers to exchange the heat from the heat transfer fluids to the water that will be used within the household. This heated water is then stored within a storage tank until it is ready for use ("Active Solar Systems, " n.d.).

Direct systems can be operated by either natural or forced convection. A natural convection, or thermosiphon system, works by drawing cold water through the solar collector while moving hot water from the collector into the storage tanks. Although this system has been proven to be simple and inexpensive, it does create two major disadvantages. First, since the system operates under natural convection, the storage tanks would need to be located at a higher point than the solar collector; which in most cases is difficult to accomplish. Second, in order for the system to work there must be water within the collector at all times leading to the possibility of freezing. In forced convection, the water circulates between the collector and the storage tank using a pump. Because the pump has the ability to be turned on and off it allows the solar collector to only operate when there is enough solar radiation to produce useful heat. Additionally, forced convection systems allow the water to be discharged by gravity flow from the collector, known as a “draindown”, to avoid freezing ("Active Solar Systems," n.d.).

Indirect systems provide more flexibility than direct systems; as they do not connect directly to the household water. As seen in Figure 10, cold water from the storage tank is drawn into the solar collector through a pump where it is heated and then returned to the storage tank. A heat exchanger within the storage tank then transfers the heat from this heated water to the cold water exiting the house’s boiler. This hot water is then available for use within the household. Similar to how the pump in the direct forced convection system, this system is controlled by an electronic controller which compares the temperature of the solar collector to the temperature of the water in the tank. When the collector is at a higher temperature than the water in the storage tank, the controller will switch on the system and begin the process of heating the fluid ("Solar Thermal Water Heating," n.d.).

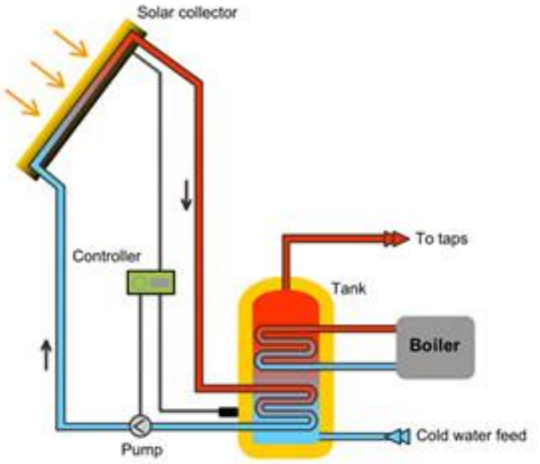


Figure 10: Indirect Solar Water Heater System

("Solar Thermal Water Heating," n.d.)

To protect this system from freezing or corroding, solutions can be added to the liquid circulating through the solar collector, such as antifreeze, which allows the system to run year round without having to drain the system ("Active Solar Systems," n.d.).

2.4.2 Geothermal Heat Transferring Systems

Geothermal systems make use of the constant underground temperature to heat and cool a space. As seen in Figure 11, the system works by running pipes that contain a heat exchange liquid underground where the liquid is either heated or cooled before it is run through a heat exchanger to either heat or cool a space (Harris, 1991). In the summer, warm air from the building is transferred into the liquid which runs deep into the ground where the temperature is cooler; heat from the liquid is then expelled into the ground and cooler liquid emerges from the ground where it is exchanged to the air within the building. In the winter the opposite occurs, where the cool air within the building is transferred into the liquid which runs deep into the ground where the temperature is warmer. This warmer temperature is then transferred to the liquid for it to be exchanged to the air within the building ("Geothermal Heating and Cooling," n.d.).

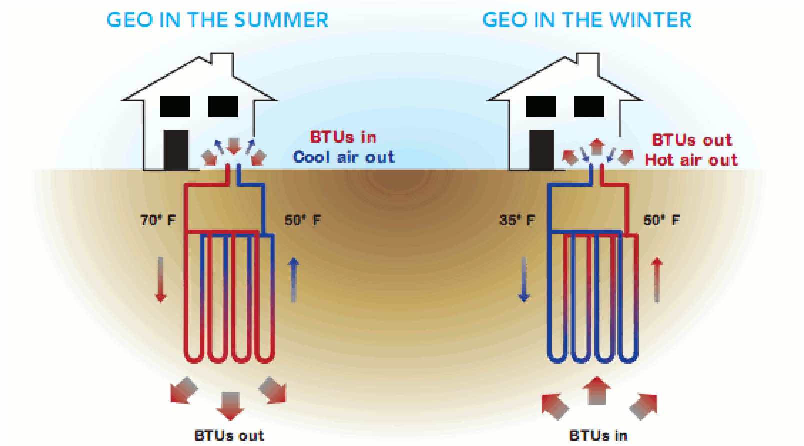


Figure 11: Geothermal System

("Geothermal Heating and Cooling," n.d.)

2.4.3 Electrical Systems

2.4.3a Traditional Electrical Systems

Electrical systems play a major role in the operation of the mechanical systems within homes. Traditionally, electricity enters a household through a service head from a series of outdoor power lines or underground connections which are fed electricity through switches and transformers located at the power plant. As seen in Figure 12, the head consists of two 120-volt wires and one neutral wire, represented by the black, red, and white wires respectively. These components are then connected to an electrical meter located outside the home which is used to measure consumption. The central distribution point for delivering power to outlets, switches, fixtures, appliances, etc. is the electrical service panel, which is fed by the power lines. For safety, all service panels are outfitted with breakers or fuses that terminate the power to the circuits within the household if an electrical failure occurs ("Understanding Your Home Electrical System," 2015).

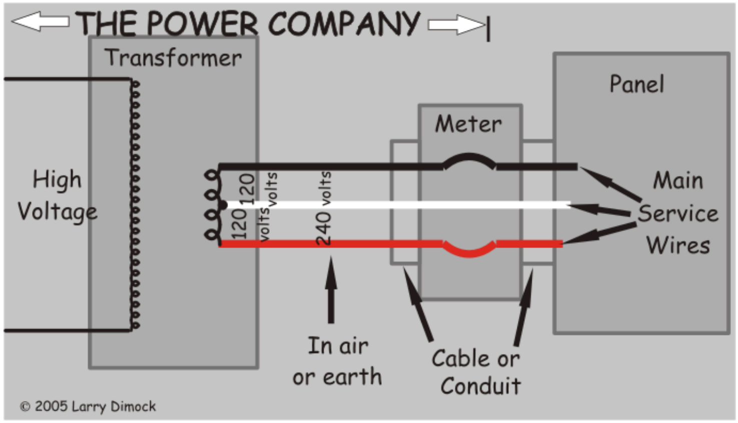


Figure 12: Typical Home Electrical Distribution System

(Dimock, 2013)

2.4.3b Photovoltaic Cells

Alternative methods to powering a home include the use of photovoltaic cells, also known as solar cells, which are used to convert sunlight to electricity. The cell converts light, which is composed of many photons, into electricity, a voltage, which is known as the Photovoltaic effect. In practice, this system reduces the reliance on external energy providers, such as the power company.

A Solar Photovoltaic panel is made out of various PV cells; these cells are semiconductor devices that convert sunlight into electricity. Seen in Figure 13, the basis for these cells is the pn junction, which is "…the junction between negatively charged N-type material that has a surplus of electrons, and positively charged P-type material that has a deficiency of electrons" ("Solar PV Technology," n.d.). The p-type semiconductor material and n-type semiconductor material, both made of silicon, are closely compacted together; in theory, the p and n type sections would be part of the same silicon crystal (Sedra & Smith, 2014). When sunlight hits the surface only the light energy that lies above the cell's energy gap will cause electrons to become "excited" and move to become part of an electric circuit ("Active Solar Systems, " n.d.).

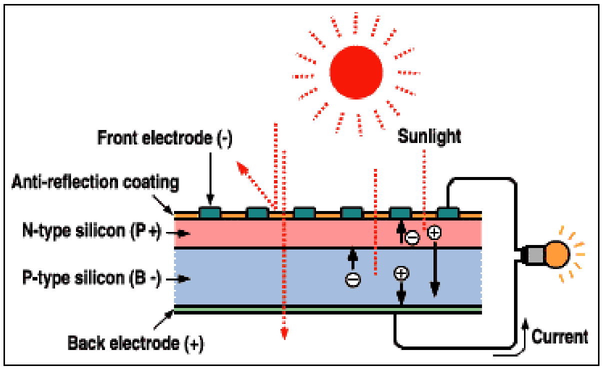


Figure 13: Photovoltaic Cell Configuration

("Solar PV Technology," n.d.)

The basic principles of photovoltaic cells have been continuously evolving and have thus far resulted in three generations of cells. The first generation of solar cells featured pn junctions made of silicon that were constructed within a flat-plate; they are the most widely used and are known to be the most efficient solar cells. Second generation solar cells were made thinner, and are therefore known as “thin-film solar cells;” they are generally made out of amorphous silicon or other non-silicon materials. Due to their thin configuration and flexibility, second generation solar cells are mainly used for rooftop shingles and tiles, building facades, or glazing for skylights. Third generation solar cells made use of new, innovative methods and materials, such as solar inks, solar dyes, conductive plastics, and high efficiency PV material. Although these solar cells are becoming more cost effective, use is limited to certain parts of the world as the lenses used within the systems must be pointed at the sun to be effective ("Solar Photovoltaic Technology Basics," n.d.).

2.5 Unity Homes

As technology advances and new standards for energy efficiency are developed, design and construction companies are rethinking the way buildings are being constructed. Focusing on residential construction, the company Unity Homes works to optimize the typical family home by aiming for an energy efficient design.

Unity Homes emerged from the company Bensonwood Woodworking, a company that builds custom timber framed houses that incorporate sustainable design into every aspect of the building process. Because custom design is expensive, Unity Homes has optimized the construction process in order to bring sustainable design to the general public while still incorporating custom components into the home. In order to fuse together a sustainable and custom design, Unity Homes has introduced construction techniques, materials and systems that differ from traditional building design and construction.

2.5.1 Design

Unlike a typical detached residential home which is designed by an architect, Unity Homes houses are built using an Open-Built® system. Developed in collaboration with a Dutch architect John Habraken, “Open-Built® is a way of approaching home design that looks at the function and usable life of six distinct interconnected layers: site, structure, skin, space plan, systems and ‘stuff ’” ("A Better Way to Build," n.d.). In addition to focusing on these six layers, Unity Homes designs its structures on a 2’ grid, referred to as an OBGrid, which allows for consistent structural and aesthetic integrity as well as making it simple to build additions in the future. Finally, Unity Homes simplifies the process by providing homebuyers with four different starting points, called platforms, which will provide them with a unique home built within a shorter time frame and at a lower cost than typical new construction homes ("A Better Way to Build," n.d.).

While the four platforms allow Unity Homes to speed up the process of both the design and construction, they can also be slightly altered to meet the needs of the homeowner. The Tradd, an abbreviation for “tradition,” is the most expensive of the four platforms with a base price of $325,000. The home is designed to resemble a classic New England “Cape” style house that has two stories and seven different sets of possible floor plans each with different numbers of bedrooms and bathrooms. They also include optional features such as screened porches, various entry styles, attached garages and one-level connectors. The platform can be built with 2-4 bedrooms and 2.5-3.5 bathrooms with a total area of 1750-2800 square feet and is best suited to feature exposed timber framing throughout the home ("A Better Way to Build," n.d.).

Figure 14: Tradd Exterior

("A Better Way to Build," n.d.)

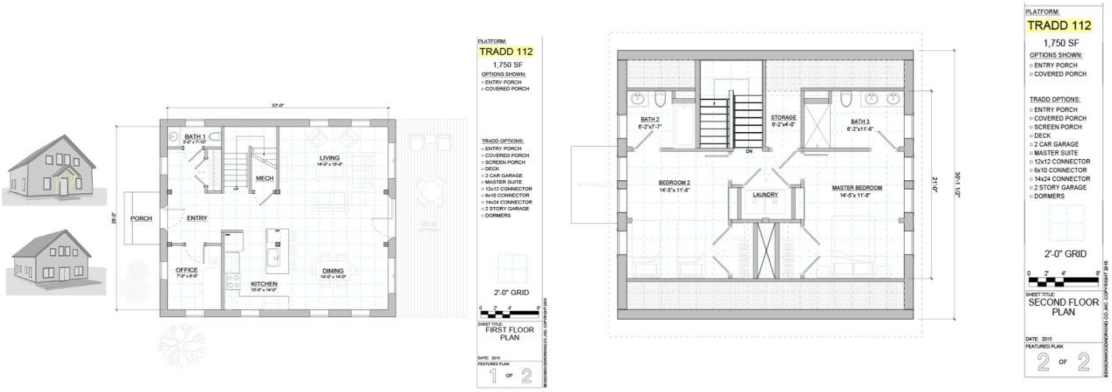


Figure 15: Tradd First (Left) and Second (Right) Level Floor Plans

("A Better Way to Build," n.d.)

The second platform, the Xyla, is a bungalow style cottage that is an extremely energy-efficient one-story space. The home can have 2-3 bedrooms and 1-2 bathrooms with a square footage range of 1100-1600. There are nine different floor plan options and can each be expanded with a garage or other separate rooms that the client desires. The base price of this platform is $200,000, but its major selling point is that it has been tested and proved to be 86% more efficient than the average American home and is almost 20% better in terms of air infiltration ("A Better Way to Build," n.d.).

Figure 16: Xyla Exterior

("A Better Way to Build," n.d.)

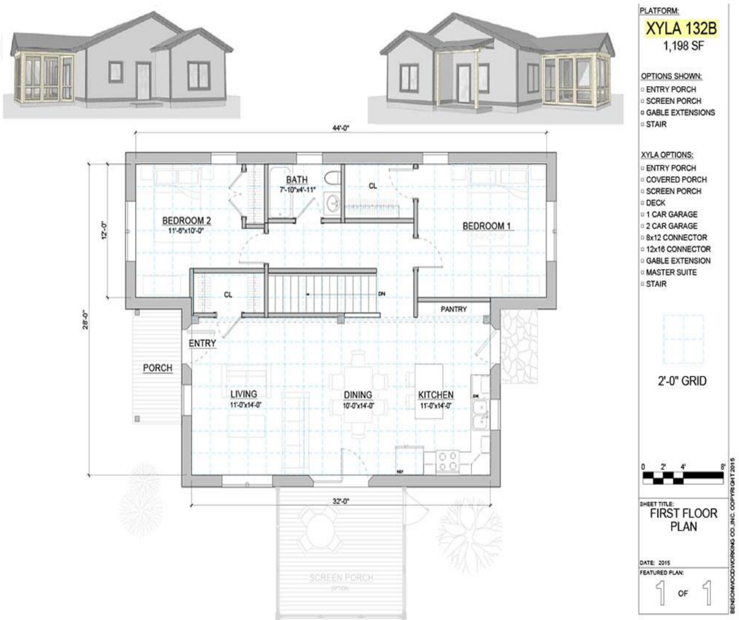


Figure 17: Xyla Floor Plan

("A Better Way to Build," n.d.)

The Värm is the most flexible of the design platforms; there are eight different floor plan options which allow for the exterior to look like a classic colonial, a country farmhouse, a basic barn or a clean modernist home. The home is also the largest of the four platforms with 1500-3000 square feet possible over two stories. It features 3-5 bedrooms and 2.5-3.5 bathrooms with a base price of $270,000. The design can also accommodate screened porches, garages and sunscreen overhangs and also lends itself to easily achieve Net-Zero energy requirements through use of photovoltaics as the Värm has a large roof area ("A Better Way to Build," n.d.).

Figure 18: Värm Exterior

("A Better Way to Build," n.d.)

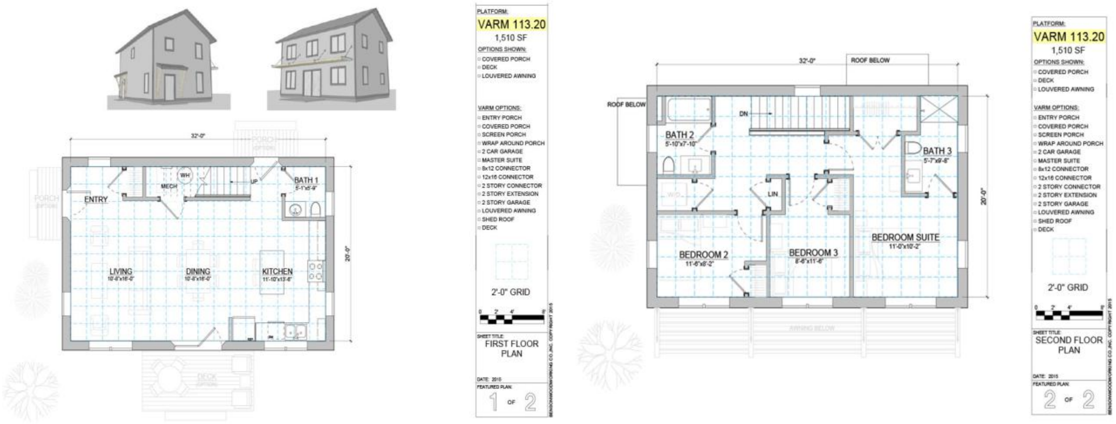


Figure 19: Värm First (Left) and Second (Right) Level Floor Plans

("A Better Way to Build," n.d.)

The final platform is the Zūm, its contemporary design has six possible floor plans that range from 1000-1700 square feet. The increase in square footage results from expanding the home horizontally where up to four bedrooms and two bathrooms can be incorporated into the design. The base price of the home is $240,000 and provides the homeowner with many benefits such as being airtight, thus eliminating drafts and outside noise and being designed and oriented to maximize natural light and solar gain allowing the temperature within the home to remain even throughout ("A Better Way to Build," n.d.).

Figure 20: Zūm Exterior

("A Better Way to Build," n.d.)

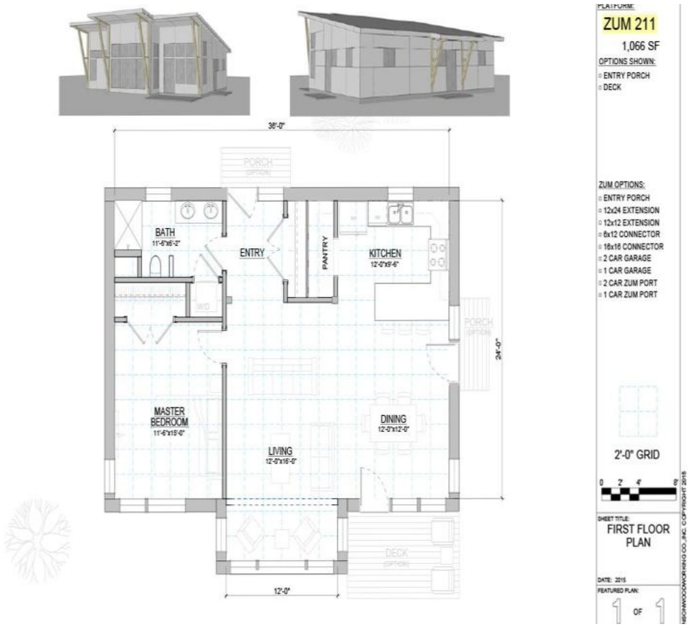


Figure 21: Zūm Floor Plan

("A Better Way to Build," n.d.)

2.5.2 Construction Process

Once the design is finalized and the 3D model is completed in the design software cadwork, the home can begin to be constructed in Unity Homes' factory. Cadwork is specially designed software that can communicate directly with the machinery in the factory in order to cut and fabricate the exact components needed for the design. Once all of the components are cut based on the design specifications, the construction team can start assembling the home. Unity Homes uses two different approaches for their off-site construction method: panelization and modular. They use modular construction exclusively for the bathrooms in the home, they are fully assembled off-site and delivered to the site with all of the fixtures, the plumbing, and the electrical wiring already installed. Because there are size restrictions for modular homes due to transportation requirements, Unity Homes constructs the rest of the home using the panelization method. They construct all of the walls, the roof and the floors in manageably sized panels that can be easily transported and assembled ("A Better Way to Build," n.d.).

Figure 22: Wall Panels Being Assembled in Unity Homes' Factory

Once the panels have been constructed, they are grouped together is such a way that once delivered, assembly can be completed in an efficient and time effective way. On-site assembly, to the point where the home is weather tight takes a few days and homeowners are able to move in between six and eight weeks after that ("A Better Way to Build," n.d.).

2.5.3 Materials

Unity Homes designs and constructs all of its homes to be durable and energy efficient. They accomplish this by using top of the line materials for the envelope of the home. A typical residential wall assembly consists of sheathing, structure, insulation and interior finish. Unity Homes uses wood as the sheathing and engineered wooden I-joists for the structural components. The use of wood in general, as opposed to steel or concrete, minimizes thermal bridging within the wall enclosure. Additionally, the I-joists have the ability to carry heavier loads with less timber and the web of the I-joist works to further reduce thermal bridging. The other component within the wall assembly that plays a major role in making a house energy efficient is the insulation. Where a typical home would have fiberglass bat insulation, or for newer homes foam insulation, within the walls and roof, Unity Homes uses dense-packed cellulose insulation. Through research Unity Homes has found that cellulose insulation delivers a greater R-value per inch than fiberglass batting and is more reliable than foam insulation ("A Better Way to Build," n.d.).

Figure 23: Wall Section

Another part of the building enclosure that contributes to the energy efficiency of the home is the windows. Windows introduce the possibility for air leakage that ultimately leads to a greater amount of energy needed to heat and cool the home. To address this, Unity Homes installs high performance, triple glazed windows that have been specifically designed for optimum performance and comfort. In addition to the use of high grade materials, Unity Homes' construction method also plays a major role in being able to produce an energy efficient home. By constructing the home panel by panel in a controlled environment there is greater attention to detail. Each panel can be assembled as seamlessly as possible, cellulose insulation can be packed as dense as possible, and where seams do exist tape can be used to completely seal the enclosure ("A Better Way to Build," n.d.).

2.5.4 Mechanical Systems

Just like a typical residential home, a Unity Home relies on mechanical systems for heating, cooling, ventilation and domestic hot water. Due to the design and construction of Unity Homes houses, they use on average 55% less energy than homes built to meet the 2009 IECC which allows them to heat and cool the entire home using a single 18k - 30k Btu Multi-Zone air source heat pump system (ASHP). Because the homes are so airtight ventilation cannot be relied on from penetration into the home, instead the homes come standard with Heat and Energy Recovery Ventilators (HRV or ERV) which recover heat and energy from exhausted air and provide filtered air into the home continuously. In addition to the use of the HRV or ERV system for ventilation, the specially designed windows can be used on a comfortable day as the ventilation source as they open into the home as opposed to typical double hung or casement windows, allowing ventilation with limited disturbance due to direct wind gusts. A system for domestic hot water is the only system that Unity Homes has yet to optimize as they are waiting for the release of a combination system that can tie in with the efficiency of the ASHP ("A Better Way to Build," n.d.).

2.5.5 Passive House Standard

As Unity Homes has strived to create energy efficient homes they can be internationally recognized as achieving this goal through the Passive House certification. “Passive House is the world’s leading standard in energy efficient construction, ” (Passive House Certification Criteria, n.d.) to meet this standard a house must meet specific criteria in five different categories. The first relates to the space heating demand where it must not exceed 15kWh annually or 10W peak demand per square meter of usable living space; a typical Unity home is about 2,000 square feet , or 185.8 square meters, which would allow the home to use 2787kWh per square meter based on the standard. Since a typical Unity home uses about 2000kW, seen in Figure 24, Unity homes meet and exceed the standard.

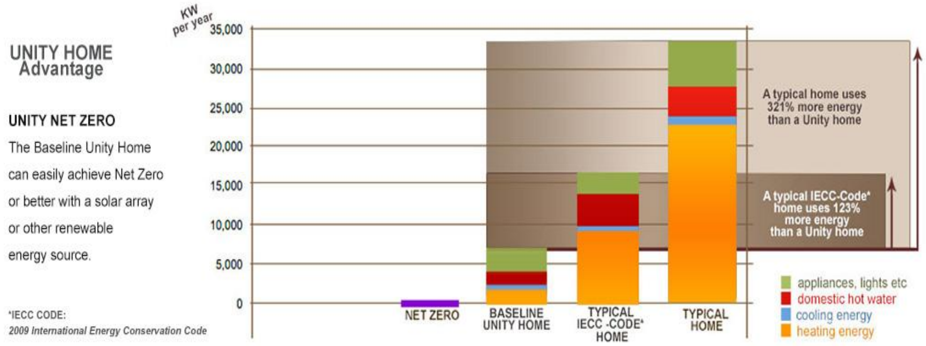


Figure 24: Typical Energy Usage in the Residential Sector

("A Better Way to Build," n.d.)

The second category relates to cooling where the space cooling demand must also not exceed 15kWh annually or 10W peak demand per square meter of usable living space, but is allowed additional use for dehumidification depending on the climate; a typical Unity home however uses a fraction of that as seen in Figure 24. The third category details the primary energy demand where all domestic applications, namely heating, cooling, hot water and electricity, must not exceed 120kWh annually. From Figure 24 it can be seen that the total energy usage is approximately 7000kWh which is much less than the allowable amount of over 22,000 based on the standard. The fourth category has to do with air tightness where there must be a maximum of .6 air changes per hour at 50 Pascals of pressure. A typical Unity home ranges from .5 to .7 air changes per hour at 50 Pascals of pressure; although Unity is able to meet the standard, this suggests that there is some room for improvement. The final category relates to thermal comfort where not more than 10% of hours in a year can the indoor temperature exceed 25 degrees Celsius, or 77 degrees Fahrenheit (Passive House Certification Criteria, n.d.). Although the indoor air temperature is ultimately determined by the occupants, when tests were conducted on Unity homes the design temperatures used were 70 degrees Fahrenheit for heating and at most 75 degrees Fahrenheit for cooling. Overall, Unity Homes has been very successful in terms of being able to meet the international passive house standard through its high quality products, impressive designs and exceptional construction methods. Although the company has met such a high standard, there is still room for improvement in terms of air tightness and a low energy combination heating, cooling, ventilation and domestic hot water system on the quest to achieve a net zero energy home.

3.0 Problem Statement and Objectives

Our project focuses on the improvement of the design and construction of the homes built by Unity Homes. During our meeting with the Operations Director of Unity Homes we were informed that there was still potential for the overall design, mainly the HVAC system, of the homes to be improved. In order to aid Unity Homes in its goal to provide affordable, energy efficient housing to the general public we analyzed their current building process and materials used and made suggestions for future improvements. We focused our efforts on the passive and active designs for the home. For the passive elements, we worked to verify the effectiveness of the construction materials used as well as the home’s orientation. As for the active systems within the home, we looked into the potential use of a solar water and thermal energy storage (TES) system to provide a cohesive, energy efficient system for the heating, ventilation, air conditioning and domestic hot water needs for the home.

4.0 Experimental Set-Up and System Functionality

In order to determine the feasibility of the use of a solar water heating system for a Unity Home, we designed and built an experimental set-up of the system. Our set-up was based on the system design that we created. Careful consideration on the placement of each component was made to ensure the desired functionality of the system. The rationality behind the sizing and placement of each component is described in Chapter 5.0 Methodology.

4.1 Experimental Set-Up

The final design of our system can be seen in Figure 25.

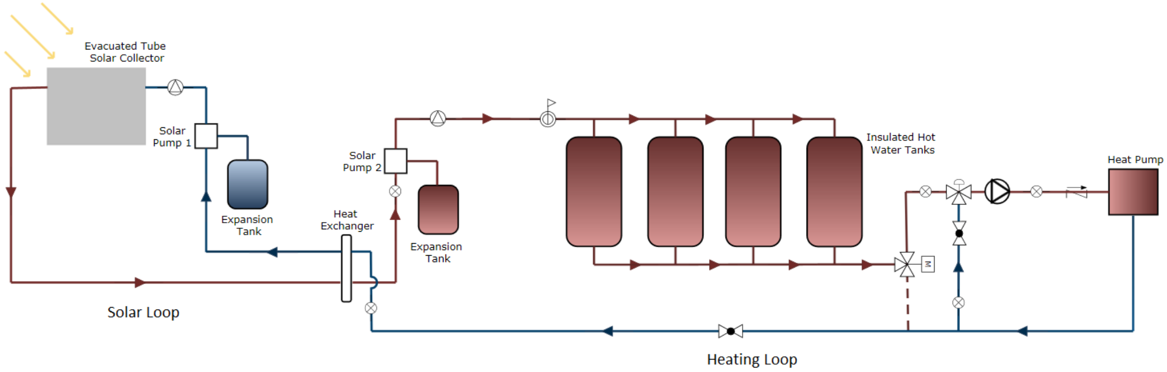


Figure 25: Solar Water Heating System Design

We began the construction of the system by assembling the evacuated tube solar collector. We first assembled the frame of the solar collector by attaching the top manifold and bottom framing piece with the three provided support posts and connection pieces. We made the connections while all of the framing pieces were flat on the ground for ease. We ensured the posts were attached at a 90 degree angle to the manifold and bottom framing piece using a square; additionally, we ensured that the middle post was exactly centered by measuring the distance from the middle post to the end post on either side.

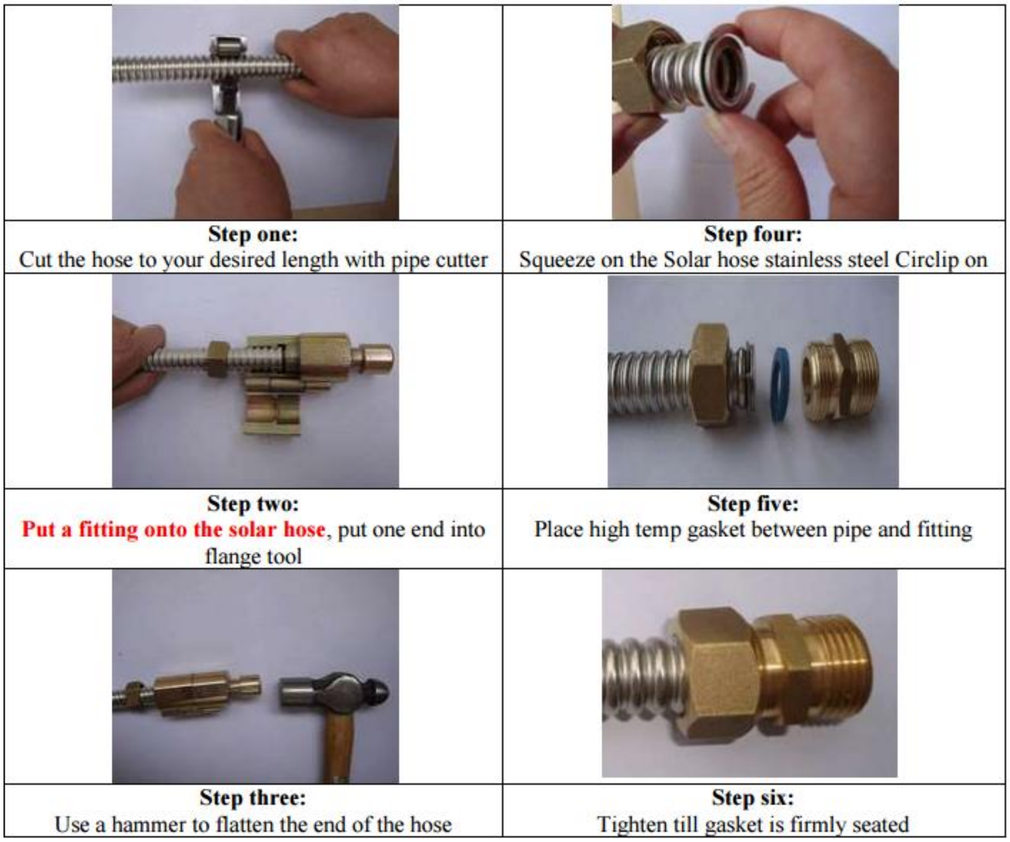
We chose to position the solar collector at a 70 degree angle and thus had to calculate where to position the supporting legs. We used trigonometry to determine where to locate the supporting leg along the posts. In order to avoid cutting the supporting legs, we performed our calculations based on the provided leg lengths. To attach the legs we positioned the frame on the ground with the back side facing up. Using our square to ensure that the legs were attached to the posts at a 90 degree angle, we had one person hold the leg in position while the other attached the connection piece. Once the three legs were attached we connected bracing elements joining the supporting legs to each other and each of the frame posts to the associated supporting leg. Finally, we attached the feet to the bottom of each of the posts and supporting legs. The fully constructed solar collector frame can be seen in Figure 26.

Figure 26: Assembled Solar Collector Frame

To attach the solar collector to the top of the trailer, we attached four 2x4's, that spanned the length of the trailer, to the rails on top of the trailer using U-shaped bolts. Two of the 2x4's provided a flat surface to connect the feet of the solar collector to and the other two, located in front of the solar collector, provided access to walk across the top of the trailer for installation and maintenance. With the help of a few people, we lifted the solar collector frame up to where two people on top of the trailer could receive and position it. We then securely fastened the frame to the roof by bolting the feet of the solar collector frame into the 2x4's. The trailer with the solar collector frame mounted to the top of it can be seen in Figure 27.

Figure 27: Solar Collector Frame Mounted to the Trailer

Using the provided flexible steel tubing, we attached two separate sections of the tubing to either side of the upper manifold using the connection method specified in the manual and depicted in Figure 28.



Step one:
Cut the hose to your desired length with pipe cutter

Step two:
Put a fitting onto the solar hose, put one end into flange tool

Step three:
Use a hammer to flatten the end of the hose

Step four:
Squeeze on the Solar hose stainless steel Circlip on

Step five:
Place high temp gasket between pipe and fitting

Step six:
Tighten till gasket is firmly seated

Figure 28: Method for Attaching Steel Tubing

(Domestic Solar Water Heating Installation Manual, n.d.)

On the input side of the collector, instead of attaching the tubing directly to the collector, we first attached the provided air vent (the air vent must be attached at the highest point in the system) which was then connected to the tubing. We ran the tubing from both sides of the solar collector into the trailer through the square air vent located in the middle of the roof of the trailer. To do this we had to remove the screen which directly exposed the inside of the trailer to outside; to avoid the infiltration of precipitation we covered the air vent with a plastic cover that we cut two holes into the side of that were just large enough to fit the tubing. To secure the cover to the trailer we attached another 2x4 along the length of the trailer and wedged three small pieces of a 2x4 between the cover and the spanning 2x4 to provide enough force to secure the cover. The resulting set up can be seen in Figure 29.

Figure 29: Running the Steel Tubing into the Trailer

We then shifted our focus to the storage drum set up. The storage drums that we purchased had two openings at the top: one ¾” and one ½” opening. Since we were using ¾” PEX piping, we had to purchase fittings to transition between ½” threaded copper to ¾” PEX. Similarly, for the ¾” hole we purchased fittings to convert ¾” threaded copper to ¾” PEX. When connecting these copper fittings, as well as the rest of the copper fittings used in the system, we ensured adequate use of Teflon to reduce the potential for leaks within the system. Once we connected the fittings for all four drums, we removed the lids to the drums and crimped PEX piping to the fittings that lead into the drums. We cut the PEX at two different lengths for the two different holes in the lid of the drums. These lengths were 1 foot and 2 ½ feet, which resulted in one pipe being close to the top of the drum and the other being close to the bottom of the drum. The result from the above described connections can be seen in Figure 30.

Figure 30: Connections Made to Drum Lid

Based on interior measurements from the trailer and the resulting length of all four of our drums aligned in a straight line, we cut Foamular rigid insulation board to create a 4” thick, coverless box around the drums. We attached the back side of the box to the side of the trailer with glue. We then attached a 2” thick Foamular rigid insulation board as a backing to a piece of plywood above the 4” thick insulation by gluing and nailing it to the side of the trailer; this set up can be seen in Figure 31.

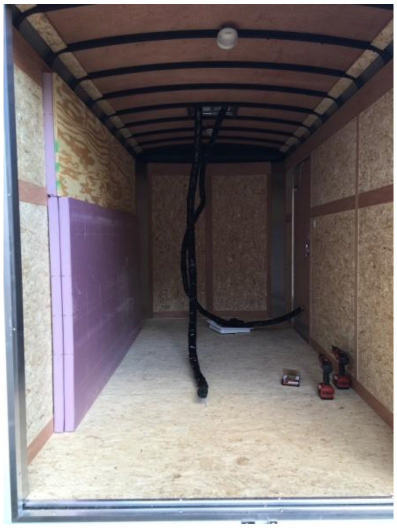


Figure 31: Insulating the Side of the Trailer

We then attached the two Wilo Star pumps at opposite ends of the plywood as well as the expansion tank for the solar loop which was placed next to the pump to be used for the solar loop. We also attached the heat exchanger to the plywood placing it in the middle between the two pumps. When attaching the heat exchanger we had to first attach a piece of wood to the plywood to ensure that both the PEX and the flexible steel tubing had enough room to be properly attached to the heat exchanger. We were then able to finish connecting all of the flexible steel tubing for the solar loop. We connected the flexible tubing that was fed into the trailer from the output of the solar collector to the "in" port on the heat exchanger. The tubing that was fed into the trailer from the input of the solar collector was connected to the output (top) of the Wilo Star pump for the solar loop. We then cut flexible steel tubing to connect the input (bottom) of the Wilo Star pump for the solar loop to the "out" port on the heat exchanger and to connect the Wilo Star pump to the expansion tank. All of the connections were made using the method depicted in Figure 28.

Once the solar loop was complete we turned our attention back to setting up the drums. We used the bottom box piece of insulation we had cut earlier as a platform to continue with our set up of the storage drums so that we could set this section of the system up indoors to avoid the cold weather. We aligned our drums on top of the insulation and began cutting pieces of PEX to connect the drums together, where the set of holes on top of the drums that had the shorter length of PEX inside the drums beneath them would be connected in a line and the other holes with the longer length of PEX inside the drums beneath them would be connected in a separate line, this set up can be seen in Figure 32.

Figure 32: Line Piping Connecting Drums

Additionally, since one length of piping will serve as the inlet and the other will serve as the outlet, one line will end in one of the end drums and the other line will end in the opposing end drum. We then crimped together all of the PEX to the fittings except for the final connection to the drums. Once we successfully attached the tanks along each set of holes and crimped together the PEX lines, we outlined the base of the drums on the insulation with a marker and labeled each drum with a number, both on the drum and next to the associated outline on the insulation. We then removed the PEX lines from the drums and the drums from the insulation and brought each of the components into the trailer. We reassembled the drums and crimped the PEX lines onto the drums. Once the drums positions were finalized, we attached the two side pieces of the insulation. Because on either end of the drums the piping extends to connect to other parts of the system, we cut holes in the insulation to allow the PEX to pass through. We then glued and nailed the side pieces of insulation to the back and bottom pieces already in place.

In order to connect the rest of the heating loop, we needed to determine where to position the heat pump. We decided to place the heat pump on the wall of the trailer opposing the tanks to be able to allow full access to the trailer and provide more wall space to build the mixing loop. We decided to build a stand for the heat pump and march pump in order to be able to position the march pump lower than the heat pump to ensure that the march pump will always be flooded with water, a requirement for its operation. Because the connection input and output on the heat pump was made of copper we had to purchase two fittings to connected copper to PEX, where the copper end of the fitting had to be soldered onto both the input and output ports of the heat pump. We were then able to make the connection between the input of the heat pump and the output of the march pump while locating both a check valve and a temperature sensor within the connecting line. Working back indoors we constructed the mixing loop on a piece of plywood. The mixing loop consisted of two lines, a main line that runs along the top of the plywood and includes a ball valve, and a second line that is directly connected to the main line by a tee connection. The second line includes the mixing valve which we attached in such a way as to create enough space between the valve and the plywood so that the top of the valve, where the valve is controlled, would be accessible. The second line also included a ball valve on the side of the mixing valve closest to the main line connection and two temperature sensors, one on either side of the mixing valve. Once the two lines were successfully connected to the plywood we brought the plywood into the trailer and mounted it to the wall, above but just in front of where the stand for the heat pump was positioned. We then connected the main line of the mixing loop to the output (top) of the heat pump and the bottom port of the mixing valve on the second line to the input of the march pump. This set-up can be seen in Figure 33.

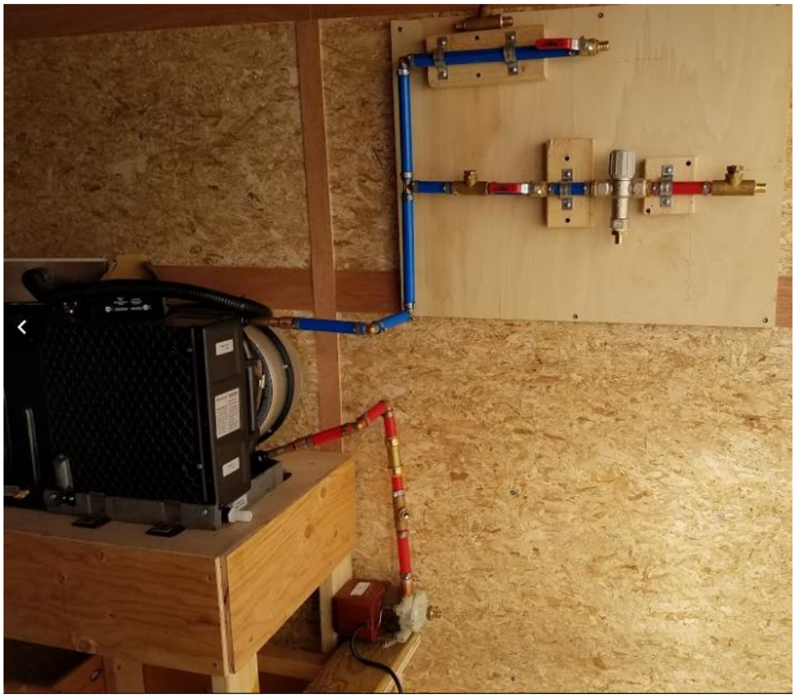


Figure 33: Heat Pump, March Pump and Mixing Loop Set-Up

In order to continue piping we needed to attach the final valve, a three-way motorized valve, to the wall of the trailer. To make connections to PEX from the three-way motorized valve we purchased fittings similar to those used for the heat pump and soldered them to the three ports on the motorized valve. We then mounted the valve to the side of the trailer using connection pieces that supported and extended the valve away from the wall of the trailer. We decided to place the motorized valve relatively low to the ground in order to run our piping along the floor of the trailer to still allow access through the trailer doors. We then connected one output port (side) of the motorized valve to the other end of the second line mixing loop. The input port (bottom) of the motorized valve was connected to the line coming off of the drums which had the long length of pipe into the drum beneath the drum connection holes. After this line passed through the insulation we first connected a pressure relief valve before connecting the line directly to the motorized valve. The final side of the motorized valve was connected to the top line of the mixing loop using a tee connection as the line also connected back to the other side of the trailer to the input port on the heat exchanger for the heating loop. We then connected the output port of the heat exchanger for the heating loop to the input of the Wilo Star pump for the heating loop, including a temperature sensor within the line. The output of the Wilo Star pump was then connected to the line attached to the tanks where the length of pipe beneath the holes on the drums was short. Finally we connected the expansion tank to the Wilo Star pump for the heating loop, which due to its size we located on the floor of the trailer behind the drums within a stand we built for it so that it would not fall over.

Once all of the piping was completed inside the trailer we installed the vacuum tubes for the solar collector. In order to install them we had one person stand on top of the trailer and had one person pass the tubes up one by one. Before each tube was passed up we covered the contact tube located at the end of each of the tubes with heat transfer paste and covered the section of the tube below the contact tube with a mixture of water and soap to allow the tube to easily slide into the upper manifold, this process can be seen in Figure 34.

Figure 34: Applying Heat Transfer Paste and Soapy Water

Once each tube was passed up, the top of the tube was inserted into the upper manifold and the bottom of the tube was then secured within the cup that attached to the bottom of the solar collector frame. Because the tubes would have started to heat up right away once they were exposed to the sun, we decided to cover the tubes with a reflective tarp which we secured to the trailer until the system was filled and able to run.

In order to fill the system we needed to provide power to all of the pumps. To ensure that the system would be safe, we acquired the help of an electrician to help us complete all of the wiring. The electrician connected the two Wilo Star pumps and the heat pump to one circuit and connected the march pump to the main control panel for the heat pump to ensure that it would always be running when the heat pump is running. The electrician also connected the RESOL DeltaSol BS Plus Solar Controller to the two Wilo Star pumps in order to obtain information that the pumps output such as temperature and pressure. Additionally, temperature sensors were placed on the top and bottom of the fourth drum, the bottom of the first drum and at the input of the upper manifold of the solar collector and then connected to the RESOL controller in order to obtain additional temperature readings. Finally, an electrical outlet and a main power supply switch were installed.

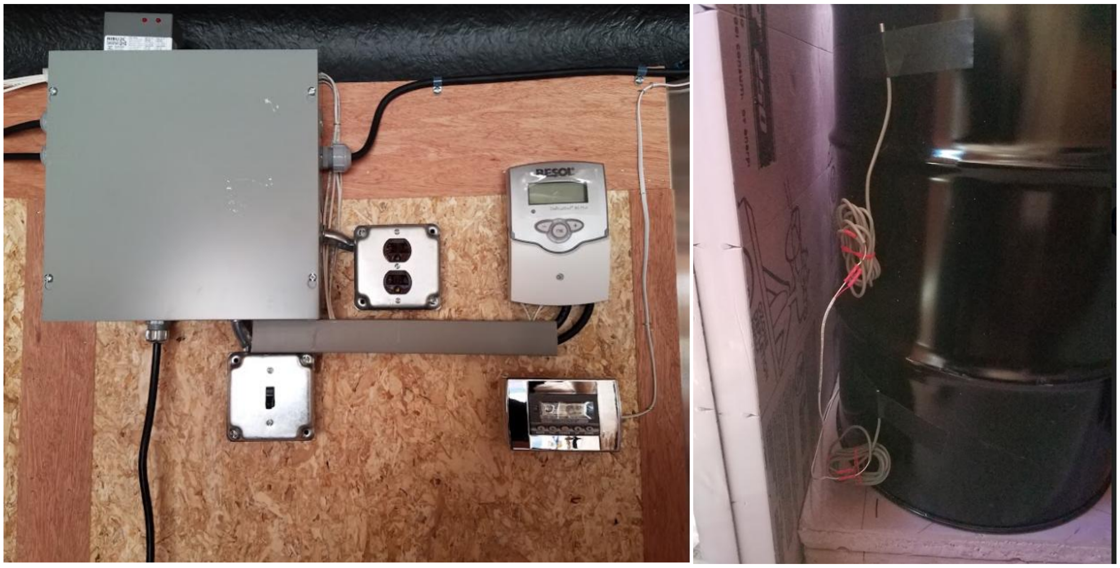


Figure 35: Electrical Set Up (Left) and Drum Temperature Sensors (Right)

The next step to completing the system set-up was filling the system. We started by filling the solar loop. We connected a clear hose to the output filling port on the Wilo Star pump for the solar loop and regular hose to the input filling port. We put the other end of the clear hose into the 5 gallon bucket of glycol that came with the solar collector. The other end of the regular hose was then connected to the output port of a small pump. We connected another length of hose to the input port of the small pump which ran to the inside of the bucket of glycol.

Figure 36: Attaching the Hose to the Wilo Star and Small Pumps

We then made sure that the flow control valve for the Wilo Star pump was closed and that both of the filling ports were open. We then turned the power on to power both the Wilo Star pump and the small pump and let the glycol circulate through the loop for about 30 minutes. As the glycol was circulating we watched the clear hose connected to the output port of the Wilo Star pump until there were no air bubbles present.

Figure 37: Glycol Bucket (Left) and Bubbles in the Clear Hose (Right)

After 30 minutes there were no longer any air bubbles exiting the loop so we closed the valve to the output of the Wilo Star pump, which caused the system to pressurize. We watched the pressure gauge on the Wilo Star pump until the pressure was not rising anymore. Based on the manual for the Wilo Star pump the pressure was supposed to read between 3.5 and 4 BAR, however our pressure stopped rising at about .333 BAR. We then turned off the power to both the Wilo Star pump and the small pump and closed the filling valve on the Wilo Star pump.

When we returned the next day to begin filling the heating loop we found that the pressure within the solar loop had dropped to zero over night. We spoke with a few experts in the field in an attempt to determine why this was happening and why the pressure was not rising to the expected level. Unable to determine why this was occurring and due to time restraints we were unable to successfully fill our system. If we had been successful in filling the solar loop we would have moved on to filling the heating loop using the exact same set-up. We purchased 55 gallons of heat transfer fluid that we were going to mix with water to prevent freezing within the system. If we were successful at filling this loop we would have then removed the reflective tarp covering the evacuated tubes and powered on the system in order to test its functionality.

4.2 System Functionality

Our system is comprised of two separate loops, which we call the solar loop and the heating loop. The solar loop contains the solar collector and one Wilo Star pump with all of the connections made using the flexible steel tubing. The solar loop contains the other Wilo Star pump, the four drums, the heat pump, the march pump, the mixing valve, and the motorized valve all connected using PEX piping. The two loops are connected through the heat exchanger, although the liquid within the two loops never touch.

The functionality of the system begins when sunlight strikes the evacuated tubes. The heat from the sun causes the gas within the tubes to rise up the length of the tubes until it reaches the base of the contact tube which we covered in heat transfer paste. The heat from the gas within the tubes is transferred to the glycol that is passing through the upper manifold of the solar collector. The heated glycol then passes through the heat exchanger where it transfers its heat to the water and glycol mixture running through the heating loop. Once the glycol in the solar loop exits the heat exchanger, it is pumped through the Wilo Star pump and back through the inlet of the solar collector where the process continues.

On the heating loop side, the functionality begins with the heated fluid that exits the heat exchanger. The heated fluid first passes through the Wilo Star pump which helps it circulate through the system. The fluid is then deposited into the four drums where the most fluid enters the first drum and the least amount of fluid enters the last drum within the line. The three way motorized valve then draws the heated fluid from the tanks, where the most fluid is drawn from the last tank in the line, the one that received the least input fluid. The motorized valve can draw the fluid through the system through two different paths which will result in either system heating or charging. The charging loop can be seen in Figure 38 where the path of the fluid is depicted by the dashed line exiting the three way motorized valve.

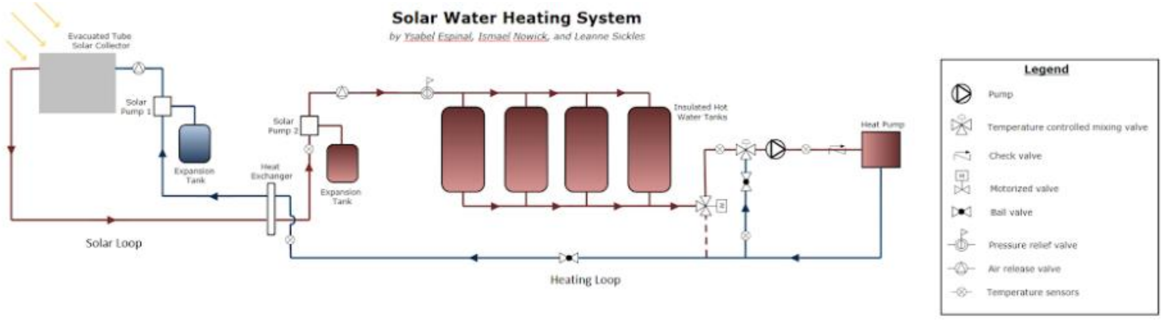


Figure 38: Solar Water Heating System Design: Charging

In this configuration, the motorized valve is set to bypass the heat pump and continue to circulate the fluid continuously through the heat exchanger in order to maintain a hot water temperature within the tanks. Alternatively, the system can be in heating mode, depicted in Figure 39 where the path of the fluid is shown as a dotted line exiting the motorized valve.

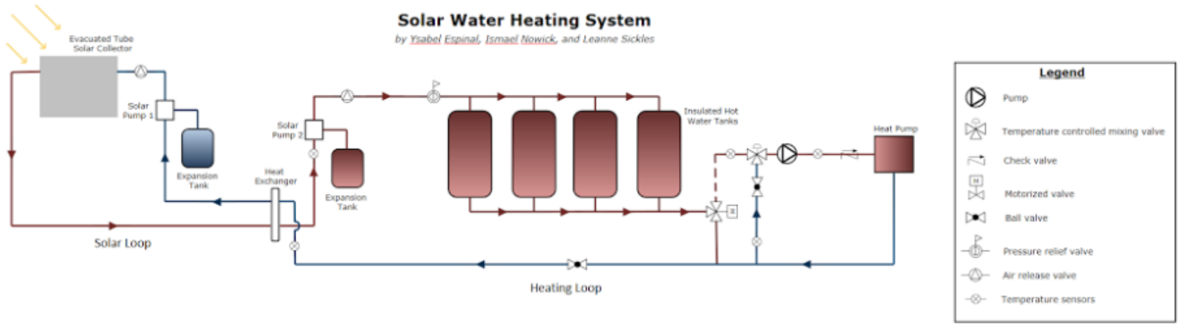


Figure 39: Solar Water Heating System Design: Heating

In this configuration, the motorized valve is set to only allow the fluid to pass through the heat pump. Upon exiting the motorized valve the fluid travels through the mixing valve where it is mixed with the cold water exiting the heat pump in order to obtain an optimal temperature for entering the heat pump. The fluid that exits the mixing valve first enters through the march pump and the check valve, to ensure that no back flow occurs, before entering the heat pump. When the fluid passes through the heat pump the heat from the fluid is transferred into the air that the heat pump blows into the air. Then now cold fluid exits the heat pump, where some of it travels through the mixing loop to mix with the entering hot water and the rest of it travels back to the heat exchanger where it is heated up and the cycle continues. Ideally, the three way motorized valve would be controlled by the heat pump where when the heat pump is triggered to turn on due to the space temperature, the motorized valve would switch to the heating phase and vice versa. Although we were not able to configure this function, we designed the system with this intention.

5.0 Methodology

In collaboration with Unity Homes, we sought to improve their home design by investigating both passive and active changes to their design. In order to complete this goal we completed the following tasks:

5. *Improve the design of a Unity Home using passive methods through simulation using energy modeling software*
6. *Design, build, and test an innovative heating system to heat a small space during the winter season*
7. *Determine the feasibility for our innovative heating system to be used within a Unity home*
8. *Develop a set of strategies and recommendations for ways to further our research and improve Unity Home's house design* both passively and actively

5.1 Objective 1: Improve the Design of a Unity Home Using Passive Methods

In order to analyze the performance of a Unity Home and identify possible areas for improvement we modeled a Unity Home that was built in Lebanon, New Hampshire. This home was designed and built based on Unity Home's Xyla platform; although many other Unity Homes have been built, we decided to focus on just one, located centrally in New England. We made this decision knowing that all Unity Homes are built to the same quality and performance standard and thus the findings in each of the platforms would be very similar.

We modeled the home with the exact dimensions and material specifications of the home that was actually built, provided to us by Unity Homes. We used the energy modeling software DesignBuilder which is a program extending from Energy Plus (E+), which is capable of simulating daylighting, weather, and HVAC conditions in order to calculate the heating and cooling loads of the modeled building. Our model of the Xyla platform can be seen in Figure 40.

Figure 40: Xyla Model

We used the software to obtain two outputs to analyze the results and the variables investigated. The first output is “district heating” which is calculated from simulating the conditions of the building’s location using weather data to calculate approximately how many kBtu of energy are required to keep the building at set point temperature, which we assumed to be 70^{o}F, throughout the year – this can also be defined as the building’s yearly heating load. The cooling load for the home was also calculated, but since our project focuses on heating the home we only considered the heating load. The district heating value is directly correlated to the cost to heat the home, where lower district heating results in a lower cost to heat the home.

The second output calculated is “design day” heating where past weather data is used to calculate a hypothetical coldest day of the year at the coldest hour of that day (potentially 3-4am). This design day heating calculation is used to size the HVAC system because the HVAC system must be able to perform and meet the set point temperature in a worst case scenario situation.

The resulting load values for the “district heating” and “design day” outputs allowed us to do two things (1) verify that the data provided to us by Unity Homes is accurate and (2) provide us with a platform to base all of our results off of. In an attempt to optimize the home’s performance we considered three variables: window type, wall R-value, and orientation. We used DesignBuilder to recalculate the home’s heating load for the two outputs after making adjustments based on our three variables.

5.2 Objective 2: Design, Build, and Test an Innovative Heating System

From our visit to Unity Homes we learned that the current HVAC and domestic hot water systems used in all Unity Homes houses are not considered to be optimal systems. Through conversations with our advisor and email exchanges with our project sponsor Ed Curtis, we decided to design, build, and test a solar water and thermal energy storage (TES) system.

5.2.1 Site Selection

We decided to build our system within a trailer owned by Worcester Polytechnic Institute’s Architectural Engineering Department as it allowed for ease of construction and gave us the ability to move the system to the ideal location. In order to have easy access to the Civil and Environmental Engineering Lab that contained all of the necessary tools as well as our professors for guidance, we decided to place the trailer outside of Worcester Polytechnic

Institute’s Kaven Hall. To obtain optimum sun exposure we placed the trailer on the south side of the building with the long side of the trailer facing exactly south. The location can be seen in Figure 41, where the site is represented by a red square.

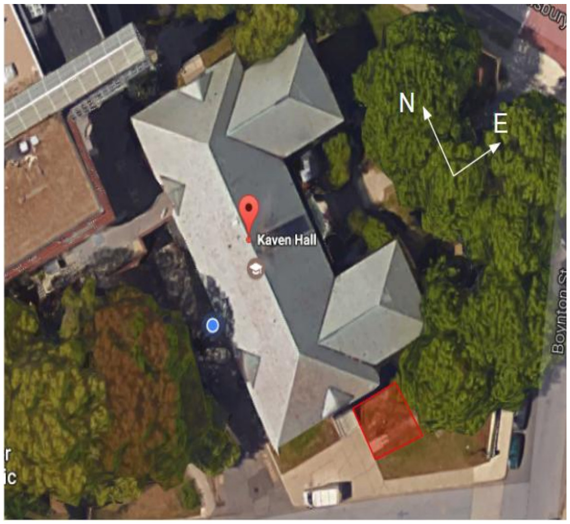


Figure 41: Project Site Location

5.2.2 Peak Heating Load Profile

In order to size the equipment, we had to consider the “worst case scenario” conditions for our geographical area. For Worcester, MA this occurs in the winter season in the month of January. Because this is the coldest month of the year, we were able to determine the maximum amount of heat that must be added to the design space in order to maintain a constant room temperature. To run these calculations we obtained meteorological data for hourly outdoor temperatures and hourly solar irradiation values. We used the data for the 21st of January as the maximum design conditions for an HVAC system are represented by a design day which is taken as the 21st of the month. In order to ensure that we were designing for the worst case scenario, we took an averaged value for the outside temperature in January and reconfigured the remaining temperatures based on the average. For example, for a design day, the average outside temperature is 6.8 °F, at a wind speed of 6.7 m/s. Therefore, we set this value equal to the lowest value in the design day and added the difference between each hourly temperature and the averaged value to set up the 24-hour temperature profile. Furthermore, we used the solar irradiation values that we obtained to determine the times of the day to calculate the heating load for as the worst case scenario is when the sun is not present, which occurs when the solar irradiance is equal to 0. Because we intended on testing the system from December through February, we decided to also look at the solar irradiation values for the months of December and February to ensure that we would be obtaining accurate values for our load profile.

In order to calculate the peak heating load we performed manual calculations which we then checked with the results from a simulated model in DesignBuilder. The processes that make up a heat balance model within a zone are split into four different categories: (1) Outside face heat balance, (2) Wall conduction process, (3) Inside face heat balance, and (4) Air heat balance. This relationship can be seen in Figure 42.

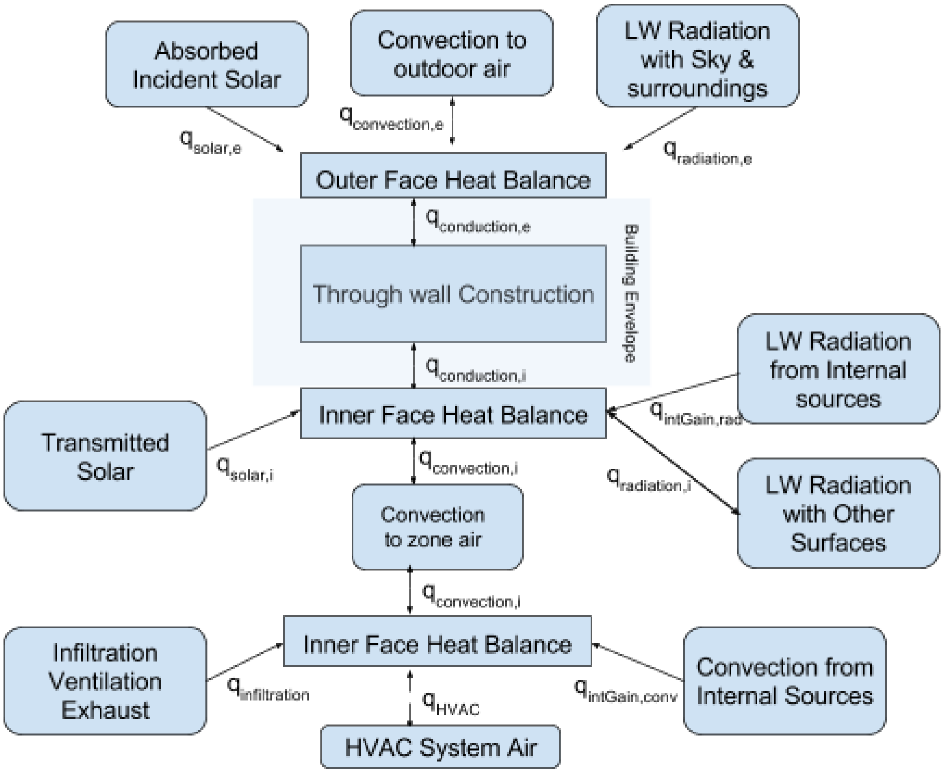


Figure 42: Heat Balance Flow Chart

(Fallahi, 2016)

Considering the following information, the heat balance model for the trailer will exhibit conductive, convective, radiation, and infiltration losses/gains. As noted before, the trailer will not exhibit solar gains due to our worst case scenario criteria. To calculate the interior and exterior losses and/or gains through the wall construction we named each surface, as seen in Figure 43.

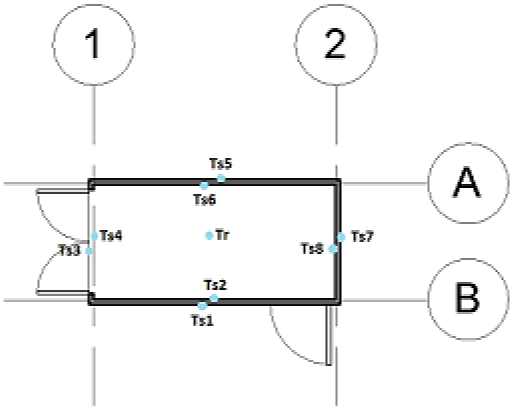


Figure 43: Trailer Wall Surfaces

The following equations represent how we calculated the heat balance for the exterior and interior walls, the average surface temperature and the heat balance at the room node. For nomenclature throughout the entirety of this Chapter see Appendix A.

The heat balance equation at the exterior wall can be expressed as:

$$\sum q = 0 = q_{conduction,e} + q_{convection,e} + q_{radiation,e}$$

Where,

$$q_{conduction,e} = U_{wall}(T_{interior\ surface} - T_{exterior\ surface})$$

$$q_{convection,e} = h_o(T_o - T_{exterior\ surface})$$

$$q_{radiation,e} = h_{r,sky}(T_{sky,y} - T_{exterior\ surface})$$

The heat balance equation at the interior wall can be expressed as:

$$\sum q = 0 = q_{conduction,i} + q_{convection,i} + q_{radiation,i}$$

Where,

$$q_{conduction,i} = U_{wall}(T_{exterior\ surface} - T_{interior\ surface})$$

$$q_{convection,i} = h_i(T_r - T_{interior\ surface})$$

$$q_{radiation,i} = h_{r,wall}(T_{avg} - T_{interior\ surface})$$

Where the equation for the area-averaged surface temperature is:

$$T_{avg} = (A_{wall}T_{interior\ surface})/(A_{wall})$$

Lastly, the heat balance equation at the room node can be expressed as:

$$\sum q = 0 = q_{convection,i} + q_{infiltration} + q_{interior\ gain} + q_{HVAC}$$

Where,

$$q_{convection,i} = A_{wall} h_i (T_{interior\ surface} - T_r)$$

$$q_{infiltration} = m_{air} C_p (T_o - T_r)$$

(Fallahi, 2016).

These equations were used to calculate each wall's interior and exterior surface temperature, the average room temperature and q_{HVAC} which is the heat needed to maintain the design space at the desired set point temperature; this list of equations can be seen in Appendix B. In order to use the equations we made the following assumptions:

- Design indoor temperature is 68 °F,
- Infiltration rate is 0.6 ACH,
- Assume there are no internal gains from any mechanical sources, lights, and people,
- Since the walls and doors are made of the same materials, assume each wall of the trailer is continuous,
- In efforts to sufficiently insulate the trailer, we are closing the hatch located on the roof; thus we will assume that the roof is continuous, and for ease of calculation, flat,
- Ignore exterior LW radiation with the surroundings (refer to Figure 42),
- Ignore thermal bridging effects, and
- Ignore latent loads.

To solve the equations, we created a matrix in excel to solve for each variable for each hourly temperature that was included in our peak heat load profile.

In addition to manual calculations, we simulated a model of the trailer in the energy modeling software DesignBuilder. We created a model of the trailer in DesignBuilder, seen in Figure 44, and indicated the wall materials, site location, heating set point temperatures, infiltration rate, and zone type. We also made the same assumptions as we did in our manual calculations when setting up the energy model. The software used weather data for Worcester, MA in order to calculate the required heating load which we then used to compare to our manual calculation.

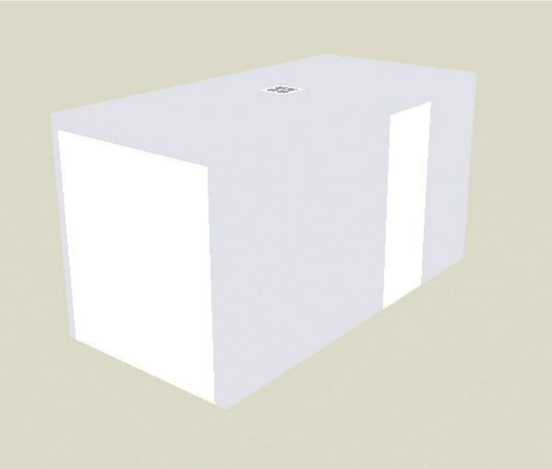


Figure 44: DesignBuilder Trailer Design

5.2.3 Materials, Equipment and Sizing

Through extensive research on solar water heating systems as well consultations with Mechanical Engineer and Worcester Polytechnic Institute Professor, Kenneth Elovitz, we created a list of all of the materials and equipment that we would need to build the system. The following sections describe the functions and methods used for sizing, if applicable, of the main components used. As in the previous section, see Appendix A for all nomenclature used throughout this section.

5.2.3a Solar Collector

From our background research we knew of the two types of solar collectors on the market: flat plate and evacuated tube. In order to achieve optimal efficiency, we decided to purchase a heat pipe evacuated tube solar collector. We purchased the solar collector from a company called Northern Lights as they sell their solar collectors in a package with all of the components needed for the construction of our solar loop.

Northern Lights sells their solar collectors in three sizes based on the number of tubes the collector has. Because there is minimal research available on the use of evacuated tube collectors for solar heating applications, to determine an appropriate collector size we adopted the use of flat plate mathematical models and evacuated tube heat pipe thermal analyses. Our methods for determining an appropriate collector size is discussed later in this chapter.

5.2.3b Heat Pump

For our application we purchased a marine heat pump which is a water to air heat pump. This pump is what allowed us to convert the heat stored in the water in our drums into the air to heat the space. This type of heat pump is normally used on boats, however its fundamental operations correspond to the principles used in our system.

In order to size the heat pump we used our results obtained from conducting our heating load profile. The manual calculations and energy modeling that we completed allowed us to determine the amount of heat per hour that is needed to heat the trailer. Instead of purchasing the heat pump based on our sizing calculation, we instead decided to purchase a heat pump that had the potential to heat a Unity Home. The Xyla house that we modeled in DesignBuilder requires 14.434 kBTU/hr based on information provided to us by Unity Homes and our energy simulation conducted for the home completed in DesignBuilder for validation. Thus, we decided to purchase a 16 kBTU/hr heat pump so that when we integrate our system into the Xyla model we would be able to see if our system could successfully heat the home.

5.2.3c Storage Drums

In order to store the hot fluid generated from the solar collector until the heat pump was activated to heat the space, we needed to purchase storage drums. To protect our system from rust and corrosion we decided to use stainless steel drums. Although we considered using one large water storage tank, we ultimately decided to use a series of smaller drums in order to create a gradual temperature difference between the drums. Additionally, smaller drums would be easier to maneuver and when considering a price per gallon we generally found the smaller drums to be cheaper.

Because we were unable to find any research similar to our system, we first sized our drums based on a basic heat transfer analysis. In order to verify our initial sizing calculations to ensure that the determined volume of fluid would be able to store the necessary heat, we completed an analysis based on a domestic hot water system set up which will be discussed later in this chapter.

5.2.3d Circulating Pumps

Our system design included three pumps in addition to the heat pump: the two Wilo Star pumps, one for each loop, and the march pump. The purpose of these three pumps was to provide circulation throughout the system, as they continuously draw fluid through them.

The Wilo Star pump for the solar loop was included in the package when we purchased the solar collector. We decided to purchase the same Wilo Star pump to be used in the heating loop for a few reasons. First, using the same pump would allow us to set the flow rate for the two loop equal to each other which will allow for maximum heat transfer between the two loops within the heat exchanger. Second, the pump includes a filling port which will allow for easy filling of the system.

The third pump that we purchased, the march pump, was used to draw the fluid exiting the mixing valve into the heat pump. This pump was purchased after ensuring that its flow rate was within the range of the variable flow rate that could be set for the two Wilo Star pumps to ensure that the fluid within the heating loop would always be flowing at the same rate.

In order to verify that the pumps that we purchased would be able to overcome the pressure drop in the system due to the piping, we calculated an anticipated length of piping and determined the number of tees and elbows needed. We accomplished this by modeling our system set up in the architectural modeling software Revit. We created two preliminary trailer designs, seen in Figure 45.

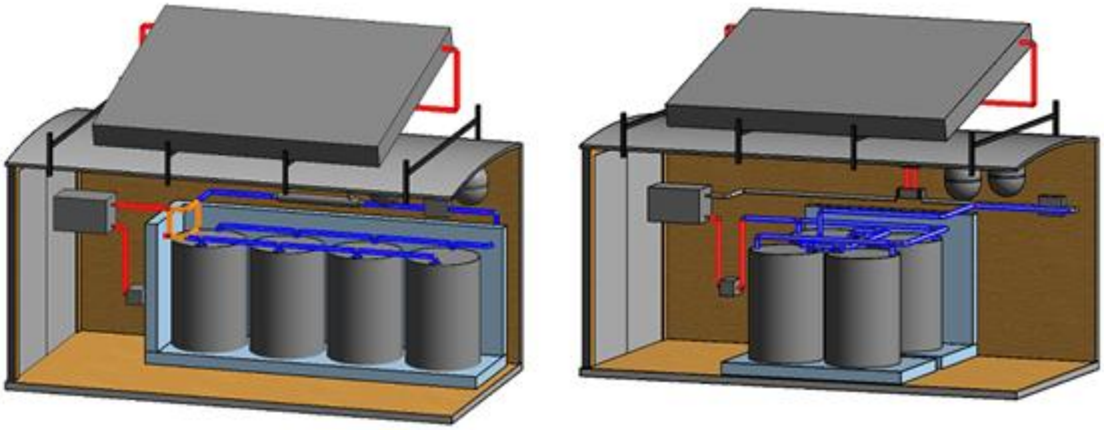


Figure 45: Preliminary Trailer Designs

We ultimately decided to use the left set up as it would allow access to the whole trailer. Using this design we were able to approximate the length of pipe and the number of tees and elbows needed. We calculated the friction head loss per 100 feet of pipe using the following equation:

$$h = .2083(\frac{100}{c})^{1.852} q^{1.852} / d_h^{4.8655}$$

We then multiplied this friction heat loss per 100 feet by the approximate length of piping in the system to obtain a total pressure drop. We added this pressure drop to the equivalent friction losses through all of the fittings and valves to obtain a final total pressure drop through the heating loop. We were then able to successfully verify that the pumps we had purchased were adequately sized. Because our Revit model turned out not to be an accurate representation of how we actually built our system, we measured the length of piping we actually used to ensure that our pumps would still be able to overcome the friction within the pipes.

5.2.3e Expansion Tanks

Our system includes the use of two expansion tanks, one for each loop. As the fluid within the two loops is heated it expands; when this occurs pressure begins to build within the system. In order to alleviate this pressure, the expansion tank provides a place for the fluid to go.

The expansion tank for the solar loop was included in the package that we purchased from Northern Lights. Thus we knew that it was appropriately sized for the system and installed it as described in our Experimental Set-Up Chapter.

To size the expansion tank for the heating loop we used the following equation:

$$V_t = \frac{(.00041t - .0466)V_g}{1 - \frac{P_f}{P_o}}$$

(Sizing the Extrol, 2014)

5.2.3f Piping

Two different types of piping were used throughout our system, one type for the solar loop and one type for the heating loop. The piping for the solar loop was included in the package with the solar collector that we purchased from Northern Lights. The provided piping was ¾” insulated, flexible steel piping. Within the insulation for the piping sensor wires were run that connect to the Wilo Star pump provided RESOL controller in order to take temperature readings. Because this piping was provided with the system, we felt confident that it was sized correctly for the system and that there was no possibility of freezing due to the combination of insulation and glycol running through the system.

For the heating loop we considered three piping materials, copper, PVC, and PEX. We ultimately decided to use PEX to pipe the heating loop as it would be the easiest to cut and make connections with. PEX piping is sold in a variety of sizes, but we decided to use 3/4” piping because it was the most readily available size and the fittings were less expensive.

5.2.3g Valves

Our system includes the use of five different types of valves. The type of valve that was used in both loops of our system was an air relief valve. As trapped air will tend to accumulate at the highest point within the system, the air relief valve was installed at the highest point for both loops within our system. Additionally, they were installed on the outflow side of the Wilo Star pumps in order to alleviate any generated air upon pump start-up.

Within our heating loop we also incorporated a pressure relief valve. As the expansion tank allows for fluid expansion as the pressure builds, the pressure relief valve is a safety feature that is activated in the event of too much pressure build up. The pressure relief valve was set to go off at a system pressure of 30 psi to prevent damage to our system components.

Our heating loop also includes two ball valves located within the mixing loop of our system. Both of these valves allow us to manually control the flow within our system in the event of a component failure.

We also included one check valve in our heating loop placed between the march pump and the heat pump. The check valve allows flow in one direction thus eliminating the potential for backflow from the heat pump.

The final valve used within our system is the three-way motorized valve. This valve, like the check valve, will only allow flow in a certain direction within our system. It will either allow the fluid to flow from the drums to the heat pump, preventing fluid exiting the heat pump from entering the stream, or bypass the heat pump and flow back through the heat exchanger.

5.2.3h Sensors

In order to acquire temperature readings to gauge how well our system is functioning, we placed temperature sensors throughout our system. The flexible steel tubing provided with the solar collector contained temperature sensing wires within the insulation of the tubing. These sensors connect to the input and output ports on both the Wilo Star pump and upper manifold of the solar collector. The RESOL controller that attaches to the Wilo Star pump then records these temperature readings based on set time intervals.

For the heating loop we purchased temperature sensors to be placed along the piping throughout the loop. We used five of these temperature sensors placing them in the following locations:

1. The output of the heat exchanger

2. The input of the mixing valve coming from the storage drums
3. The input of the mixing valve coming from the output of the heat pump
4. The output of the mixing valve
5. The input of the heat exchanger

In order to obtain temperature readings from the fluid within the drums, we attached temperature sensors to the exterior of the drums. Because we were interested in the temperature difference between the top and bottom of the drums as well as between the first and last drum within the series connection, we placed these temperature sensors in the following locations:

1. The bottom of the first drum
2. The bottom of the fourth drum
3. The top of the fourth drum

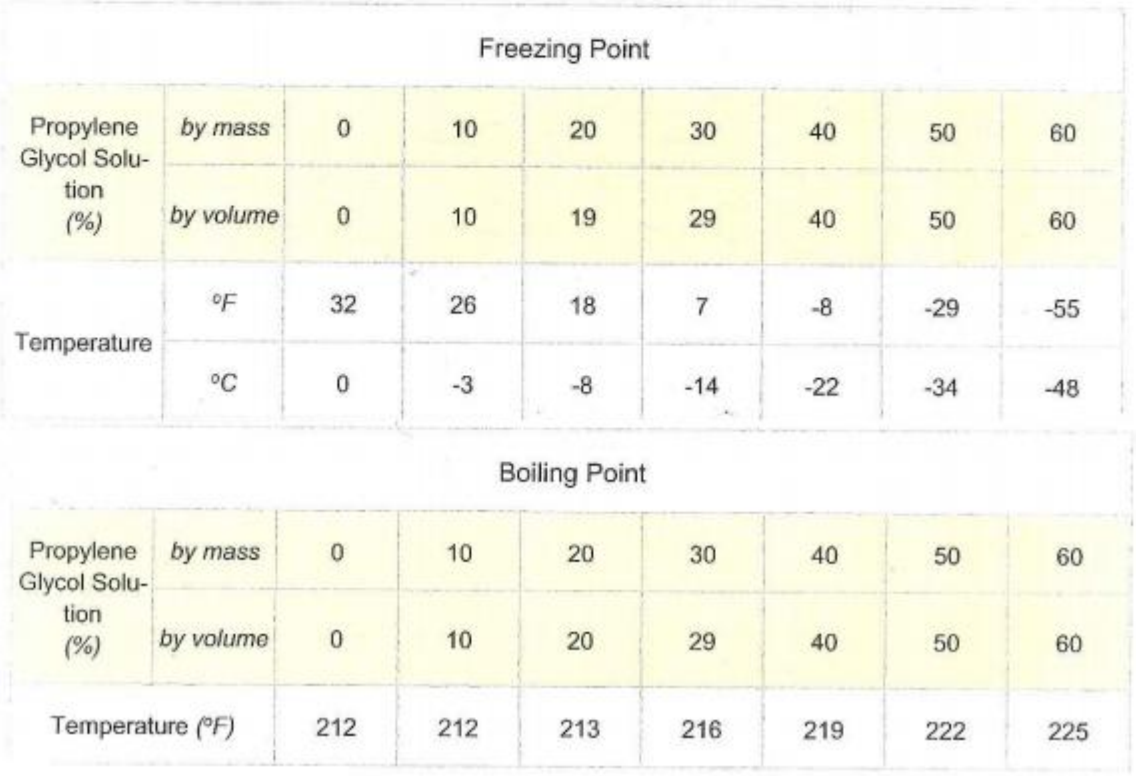
To have access to these temperature readings we intended to connect all of the sensors to a controller, much like the RESOL controller. However, due to time constraints and lack of electrical knowledge we were unable to connect the sensors.

5.2.3i Insulation

Because we built our system within a poorly insulated trailer and it is intended to be used throughout the winter season, we decided to install insulation to decrease the potential for freezing within the pipes and reduce the heat loss from the drums. We purchased 4’x8’x2” sheets of Foamular rigid insulation board to insulate our system. Although we had other options, rigid board insulation would be the easiest to work with and it was the most cost effective choice based on the provided R-value. We installed a single layer of the insulation board behind the plywood that we mounted our two Wilo Star pumps and heat exchanger on in order to prevent damage to the pumps. To insulate the drums, we decided to glue two sheets of the rigid board insulation together to provide a greater R-value, as we were anticipating there to be a lot of heat loss off the drums. We cut the insulation board to create a box around the drums. Because we were not able to successfully fill our system, we did not install the front side of cover to the box; however, we were planning on creating a trapezoidal cover, as opposed to a flat cover, in order to enclose the two Wilo Star pumps and the heat exchanger to provide increased protection from freezing.

5.2.3j Fluids

As an additional measure to prevent freezing within the pipes, both our solar and heating loops were intended to be filled with a glycol and water mixture. With the solar collector that we purchased came a five gallon bucket of pre-mixed propylene glycol. The manual for the solar collector included a table relating the ratio of glycol in the mixture to respective operable temperature ranges, seen in Figure 46.



Freezing Point								
Propylene Glycol Solution (%)	*by mass*	0	10	20	30	40	50	60
	by volume	0	10	19	29	40	50	60
Temperature	°F	32	26	18	7	-8	-29	-55
	°C	0	-3	-8	-14	-22	-34	-48

Boiling Point								
Propylene Glycol Solution (%)	*by mass*	0	10	20	30	40	50	60
	by volume	0	10	20	29	40	50	60
Temperature (°F)		212	212	213	216	219	222	225

Figure 46: Freezing and Boiling Points of Propylene Glycol Solution

Because the system came with a pre-mixed 50/50 glycol to water mixture and the temperature range presented in the table was fitting to New England, we decided not to further mix the solution.

Because we also wanted to use a glycol mixture within our heating loop, we calculated the volume of fluid within the loop and used the same table to choose an appropriate ratio. We calculated the volume of the heating loop, which included the volume of the drums plus the volume of all of the piping.

5.2.5 Creating a Mathematical Model

In order to determine the feasibility of our design and verify our storage drum sizing was adequate, we decided to follow a mathematical model established Engineers from the Indian Institute of Technology. Although their model was based on the use of a flat plate solar collector for a domestic hot water system, we thought it would provide a good approximation for our system. Their system was set up so that the hot water produced by the solar collector would be stored in a storage tank until it is withdrawn to be further heated to meet the load demand through an auxiliary heater and then supplied to the space with cold water returning into the storage tank. Because our system includes the use of an evacuated tube solar collector and the fluid entering the storage tanks is assumed to always be heated, we made adjustments to our input values to account for these differences.

We began our analysis by setting up an energy balance equation for our system:

$$\left(\rho C_p V_{st}\right)\frac{dT_{st}}{dt} = q_s - q_{Ls} - q_{stl}$$

Where q_s represents the solar useful heat gain rate from the solar collector and can be calculated using the following equation:

$$q_s = A_c[G_T F_R(\tau\alpha) - F_R U_L(T_{st} - T_a)]^+$$

Here the plus sign indicates that only positive values obtained from the equation are considered as the solar collector is only providing useful heat when the sun is out. Upon solving this equation for a design day we found that positive values resulted between hours 8 and 16 and negative values resulted between hours 1 and 7 and hours 17 and 24. The next value, q_{Ls}, represents the load met by solar energy and can be calculated using the following equation:

$$q_{Ls} = \dot{m}_L C_p(T_{st} - T_R)$$

Finally, q_{stl} represents the rate of storage loss and can be calculated using the following equation:

$$q_{stl} = U_{st}A_{st}(T_{st} - T_a)$$

(Kulkami, 2006).

The mathematical model that we followed then solved the differential equation which resulted in four different cases to be used depending on the storage fluid temperature compared to the desired storage fluid temperature as well as the values calculated earlier for the useful heat gain rate from the solar collector. Because our system is set up with the intension of having the storage fluid temperature be greater than the desired storage fluid temperature, or temperature exiting the storage drums, we used the first two cases as follows:

Case I $(T_{st} > T_L)$ *and* $q_s > 0$*:*

$$\frac{[A_c I_T F_R(\tau\alpha) - A_c F_R U_L\left(T_{stf} - T_a\right) - \dot{m}_L C_p(T_L - T_R) - U_{st} A_{st}(T_{stf} - T_a)]}{[A_c I_T F_R(\tau\alpha) - A_c F_R U_L(T_{sti} - T_a) - \dot{m}_L C_p(T_L - T_R) - U_{st} A_{st}(T_{sti} - T_a)]} = \exp\,(-\frac{(A_c F_R U_L + U_{st} A_{st})t}{\rho C_p V_{st}})$$

Case II $(T_{st} > T_L)$ $\;and\; q_s \leq 0$*:*

$$\frac{[-\dot{m}_L C_p(T_L - T_R) - U_{st} A_{st}(T_{stf} - T_a)]}{[-\dot{m}_L C_p(T_L - T_R) - U_{st} A_{st}(T_{sti} - T_a)]} = \exp\,(-\frac{(U_{st} A_{st})t}{\rho C_p V_{st}})$$

(Kulkami, 2006).

Based on our results from calculating the useful heat gain rate from the solar collector we determined that Case I should be used for hours 8 through 16 and Case II should be used for hours 1 through 7 and hours 17 through 24. Based on weather data from Energy Plus, we solved for the final storage fluid temperature, or the storage fluid temperature at the end of the day, for each hour of the day for the first 24 days in the month of January and obtained the following graph:

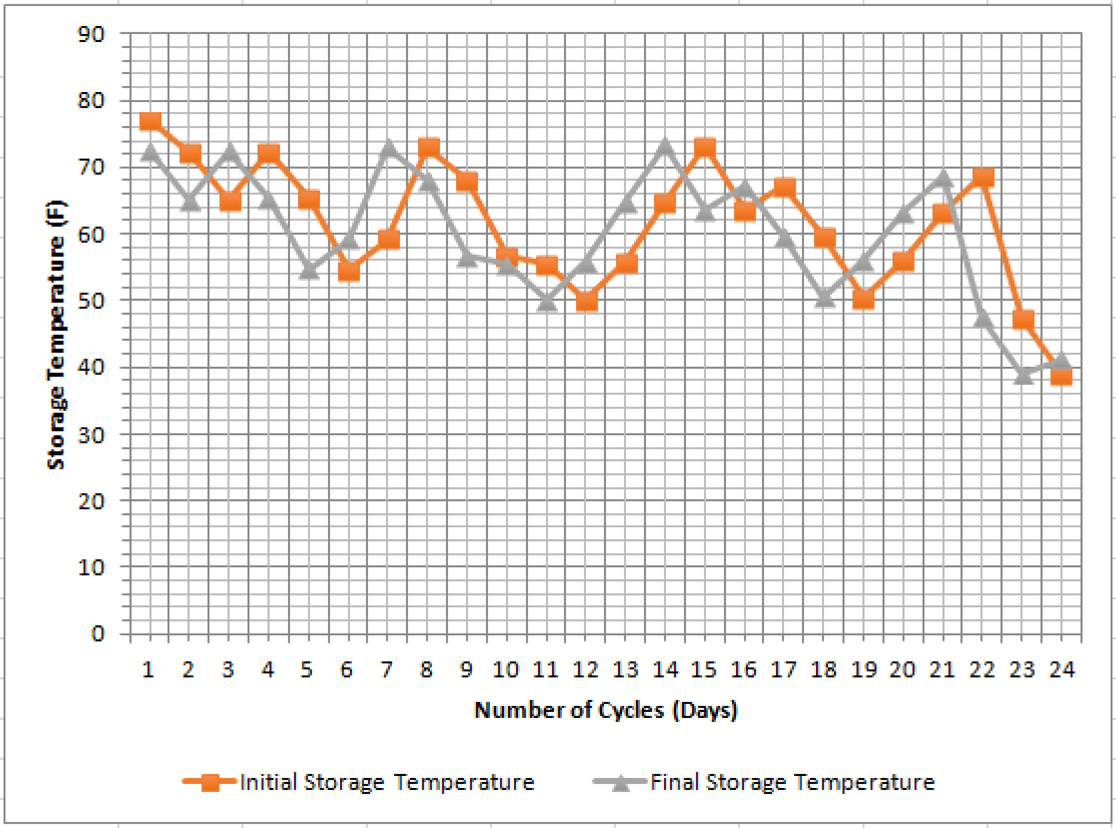


Figure 47: Fluid Temperature within Storage Drums for a 24 Day Cycle (attempt 1)

In the graph, the initial storage temperature represents the fluid temperature at the start of the day and the final storage temperature represents the fluid temperature at the end of the day, where the initial storage temperature was taken as the final storage temperature of the previous day. Due to the changing outdoor temperature, which we assumed to be the ambient temperature of the trailer, there was a lot of fluctuation in the fluid temperature. Because the fluid temperature never fell below the freezing point of the glycol and water mixture we concluded that our system was successful. However, upon further review of our calculations we realized that one of our original assumptions was incorrect. By assuming that the outdoor temperature was always the temperature inside the trailer we were not considering the fact that the trailer was being heated.

To account for this mistake we performed our calculations again assuming the ambient temperature of the trailer was always our set point temperature of 68°F. We then obtained the following graph:

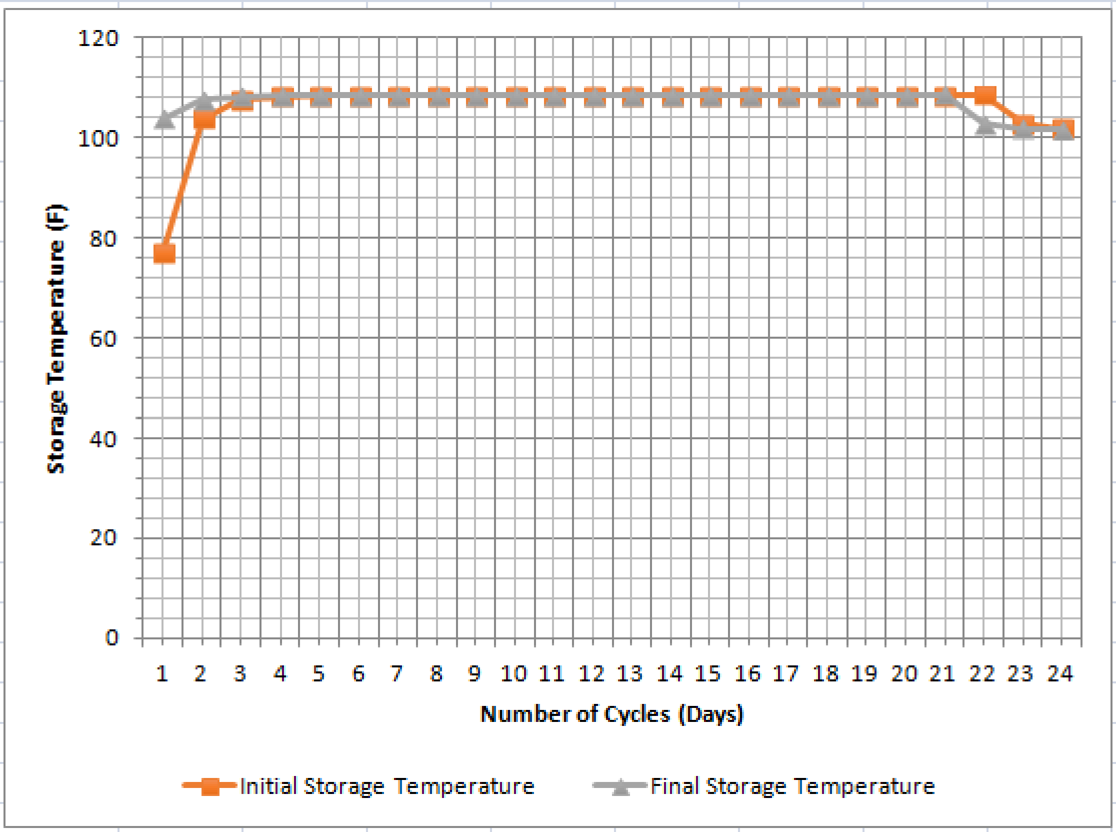


Figure 48: Fluid Temperature within Storage Drums for a 24 Day Cycle (attempt 2)

Although these results seemed reasonable as the temperature of the fluid maintains a consistent temperature that is above the set point temperature, we ultimately realized that our model does not take into account the heat loss through the walls of the trailer.

To account for this, we used Designbuilder to obtain heating load values for the trailer for every hour of the day over the first ten days of January. We then reanalyzed each component of the Case I and Case II equations to obtain accurate results. The right side of the energy balance equation that we started our mathematical model with accounts for all of the heat gains and losses within the system. The first term, q_s includes the heat gain due to the solar collector and also the heat loss as the hot fluid travels from the solar collector to the storage drums. Because there is also heat gain and loss through the solar loop of our system we kept the q_s term the same for our calculations. After passing through the solar collector however, there is a difference between our system set up and the system that the mathematical model is based on. In the original system, after passing through the solar collector the fluid runs directly into the storage drum, but in our system the fluid exiting the solar collector passes through a heat exchanger and transfers the heat to the fluid running though the heating loop. Because the heat is being transferred there is potential for additional heat loss within the system. In an attempt to account for this loss, we researched our heat exchanger and received a specification sheet from Northern Lights but we were unable to obtain the necessary information to calculate its efficiency. Our research did however reveal that our heat exchanger is one of the most efficient heat exchangers on the market. Based on all of this information, we ultimately decided to neglect the heat loss due to the heat exchanger.

The second term in the energy balance equation, q_{Ls} represents the demand of the system. In the original model, once the fluid exits the storage drum it enters an auxiliary heater where it is further heated to meet the domestic hot water desired temperature where within the term T_L represents the desired load temperature and T_R is the temperature of the water returning to the tanks. In our system, the auxiliary heater is essentially our mixing loop where the hot fluid from the drums is cooled to the desired temperature to enter the heat pump. The fluid that returns to the drums however will be different depending on the time of day. When the sun is not out, and the solar loop is not running, the returning fluid temperature will be the temperature of the fluid leaving the heat pump. When the sun is out and the solar loop is running, the fluid exiting the heat pump will first pass through the heat exchanger where it will be heated before returning to the storage drums. Because our system's demand is directly affected by the temperature of the trailer, we added a term to the q_{Ls} equation to account for the heat loss through the walls of the trailer. To do this, we obtained heat loss values for each hour of the day over a ten day period from Designbuilder based on outdoor air temperature. We then subtracted these values within the q_{Ls} term of the energy balance equation.

The final term in the energy balance equation, q_{stl} represents the heat loss from the storage drums. Because we expect there to be heat loss through the drums even with the presence of the insulation we made no changes to this term.

Based on this analysis, our resulting Case I and Case II equations are as follows:

Case I $(T_{st} > T_L)$ *and* $q_s > 0$*:*

$$\frac{[A_c I_T F_R(\tau\alpha) - A_c F_R U_L\left(T_{stf} - T_a\right) - \dot{m}_L C_p(T_L - T_R) - q_{tailer} - U_{st}A_{st}(T_{stf} - T_a)]}{[A_c I_T F_R(\tau\alpha) - A_c F_R U_L(T_{sti} - T_a) - \dot{m}_L C_p(T_L - T_R) - q_{trailer} - U_{st}A_{st}(T_{sti} - T_a)]}$$

$$= \exp\left(-\frac{(A_c F_R U_L + U_{st}A_{st})t}{\rho C_p V_{st}}\right)$$

Case II $(T_{st} > T_L)$ *and* $q_s \leq 0$*:*

$$\frac{[-\dot{m}_L C_p(T_L - T_R) - q_{trailer} - U_{st}A_{st}(T_{stf} - T_a)]}{[-\dot{m}_L C_p(T_L - T_R) - q_{trailer} - U_{st}A_{st}(T_{sti} - T_a)]} = \exp\left(-\frac{(U_{st}A_{st})t}{\rho C_p V_{st}}\right)$$

We then solved for the final storage temperature and graphed the results. Our resulting graph suggested that our system was not properly sized and in order to determine the best collector and drum sizes we adjusted their values until a reasonable graph resulted. Because the heat pump can run in heating mode at input temperatures between 40^{o}F and 77^{o}F, we assumed a reasonable graph to be one in which the temperature within the drums never dropped below 40^{o}F.

5.2.6 System Design

Our system design was created through a combination of research and a series of consultations with Professor Elovitz. Because the solar collector that we purchased also included all of the components needed for the solar loop, that part of our system design was based on the system set up provided to us by Northern Lights. For our heating loop we created many iterations of the design and each time had it reviewed by Professor Elovitz. Our first iteration consisted of the four hot water storage drums connected to the heat exchanger and heat pump on either side. It was then decided that additional circulating pumps would be necessary and the introduction of a pressure relief valve and air relief valve should be made. We talked through the location of the pumps and valves and also discussed the need for an expansion tank. As these components were incorporated to increase the safety of the system, we also considered how hot the fluid in the drums could potentially become and looked into the maximum operating temperature of the heat pump. We found the maximum fluid temperature intake on the heat pump to be 77^{o}F which was a lot lower than our anticipated storage fluid temperature. To account for this we formulated the idea of incorporating a mixing valve to mix the incoming hot fluid with the cold fluid exiting the heat pump in order to obtain the optimal temperature. We then considered that the heat pump will most likely not be needed to continuously heat at all times, thus we incorporated the three way motorized valve to create two separate system modes: heating and charging. Finally, we discussed the inclusion of check valves and ball valves in order to prevent backflow and be able to manually restrict flow. Our final system design, as well as an explanation on how our system functions is presented in Chapter 4.0.

5.2.7 System Construction

Section 4.1 in the previous chapter describes the construction of our system. In order to carry out the construction we completed work together as a team, in pairs, and individually.

5.2.8 Electrical Design and Controls

In order to provide power to our system, we collected data on each of the components that required power. These components were the two Wilo Star pumps, the march pump, the heat pump and the three-way motorized valve. Once we obtained this data, we enlisted the help of an electrician to help us install the electrical components in a safe manner.

Because our system design requires some of the components to run while others may not need to, we also drafted a pump schedule for the pumps and motorized valve. We accomplished this by determining (1) when each pump would be on, (2) if there were time and/or temperature restrictions, and (3) which pumps are dependent on each other. In order to implement our design with a control system we had our design reviewed by a professor in the Electrical Engineering department at WPI. Upon showing him our plan and explaining how the system is intended to work, he informed us that our system requires a more complex control plan, one that our collective knowledge would not allow. We sought help from a couple of different experts in the field, but were unable to completely solve our problem in the time allotted for the project. However, for the purposes of this project, we included a tentative control schematic that could be pursued in the future.

5.3 Objective 3: Feasibility of Unity Home Integration

Using the original model that we designed in DesignBuilder for the Xyla platform and our DesignBuilder model for our solar water heating system we aimed to predict the effectiveness of our system within a Unity Home. We attempted this by changing the HVAC settings within the program for our model of the Xyla platform from simple to detailed. In doing so, DesignBuilder calculates loads differently; instead of using an idealized HVAC system that always reaches the defined set point temperature, as the system does when the HVAC is set to simple, the components of our system were inserted and the system was run until it reached the set point temperature. Upon running this simulation, DesignBuilder outputs data on how the system performed, which includes a table depicting how many hours throughout the day our system was not able to reach the defined set point temperature. These results would allow us to determine if our system is a feasible option for a Unity Home.

In addition to using DesignBuilder, we also our mathematical model established in Objective 2. We made adjustments to our model by inputting values associated with the Xyla platform and again changed the solar collector size and storage drum volume until we obtained an adequately sized system to meet the demand required by the home.

5.4 Objective 4: Develop a Set of Strategies and Recommendations

Using information gathered from our background research, energy modeling and the construction of our system we were able to make recommendations for Unity Homes and for future WPI students. From our energy modeling to investigate the potential for passive improvements to Unity Home’s houses we were able to make definitive conclusions about their design and construction process and formulated recommendations to reflect our findings. The design and testing of our system within the trailer and in DesignBuilder revealed potential flaws with the system which allowed us to prepare recommendations on how to improve the system. Additionally, we developed ideas on how to improve our system that could be implemented by WPI students in future projects. Finally, our system integration with a Unity Homes house allowed us to analyze the potential of our system for use within a home and helped us develop recommendations on the system’s integration.

6.0 Results

The following Chapter presents our results from each of our objectives as described in our Methodology chapter.

6.1 Objective 1: Improve the Design of a Unity Home Using Passive Methods

Windows

Error! Reference source not found. shows the district heating and design day load of the home for four different window types.

Table 1: Comparison of Window Types

	Base Design (Trp low-e (e2=.2) Clr 3mm/13mm)	Double Pane (Dbl low-e (e2=.2) Clr 3mm/13mm Air)	Triple Pane w/ film (Trp Bronze [44] 6mm/6mm Arg)	Quadruple Pane (Qdp low-e 3mm/8mm Krypton)
District Heating (kBtu/year)	16351	17836	20775	16454
Design Day (kBtu/h)	15.44	18.16	16.43	15.42

In all of their homes Unity Homes use low-e triple pane windows which are represented by the "Base Design" column in the table. Although we found that the quadruple pane window is better at holding in heat, resulting in less heat required on a design day, using quadruple pane windows results in a greater district heating load. This occurs because quadruple pane windows block out more sunlight resulting in less passive heat gain from the sun which ultimately requires an increase in mechanical heating. Because of this the triple pane low-e windows that Unity Homes already use are the most efficient and cost effective option from what we have tested.

Insulation

Error! Reference source not found. shows the district heating and design day load of the home for four different R-value wall insulations.

Table 2: Comparison of Wall Insulation

	R-31 (Base)	R-36	R-41	R-26
District Heating (kBtu/year)	16351	15902	15527	17013
Design Day (kBtu/h)	15.44	15.12	14.85	15.92

In their wall and roof construction Unity Homes uses dense-packed cellulose insulation to achieve an R-31 value. As we found, improving the R-value of the walls will improve the efficiency of the home because less heat is lost through conduction through the home's envelope. The R-value can be improved in one of two ways, changing the insulation type or increasing the insulation thickness. The insulation that Unity Homes currently uses in their homes is roughly equivalent to the insulations currently on the market, thus in order to achieve the greater R-value insulation that we investigated Unity Homes would have to increase the thickness of their walls. However, the cost of implementing a greater R-value insulation may be larger than the savings generated by the improved insulation value. We have thus concluded that the most efficient and cost effective insulation for Unity Homes walls is the R-31 dense-packed cellulose insulation.

Orientation

Error! Reference source not found. shows the district heating and design day load of the home when oriented eight different ways.

Table 3: Comparison of Home Orientation

Rotation (Degrees)	(Base) [0, 360]	45	90	135	180	225	270	315
District Heating (kBtu/year)	16351	16803	17066	17015	16970	17424	17354	16825
Design Day (kBtu/h)	15.44	15.44	15.47	15.47	15.47	15.47	15.47	15.44

The house's current orientation, represented by the "base" column in the table is depicted in Figure 49 where the arrow points north and the south facing side of the building is the side with the most glazing area.

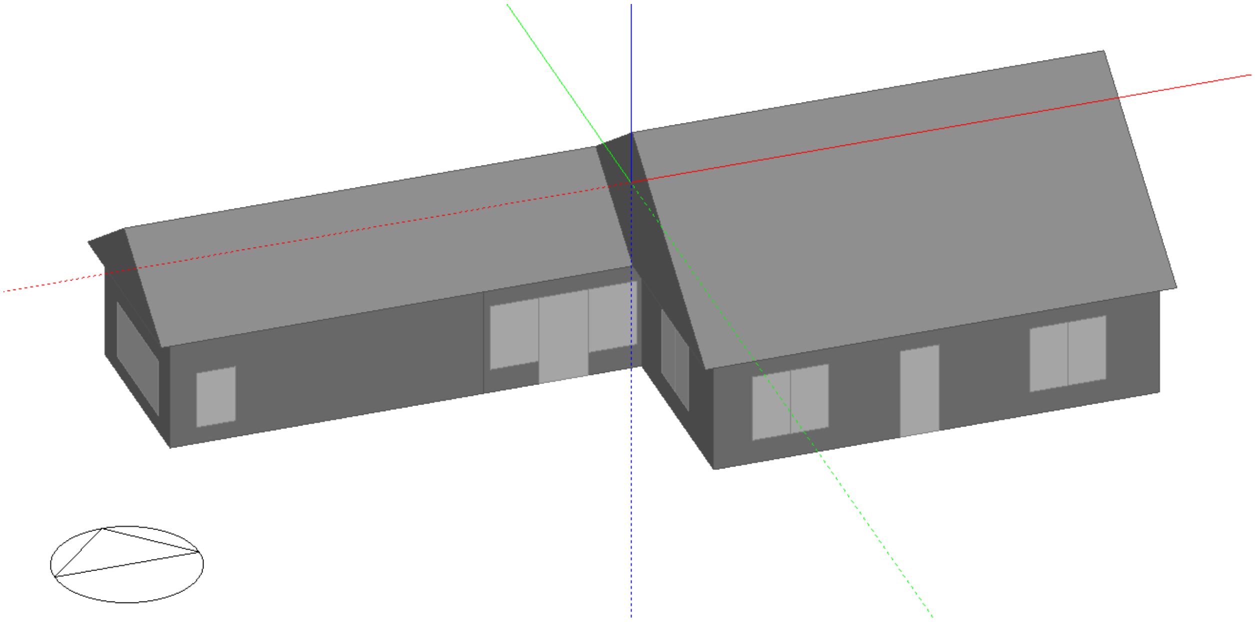


Figure 49: Home Base Orientation

From the base design, the home's load was recalculated at 45 degree intervals going counter-clockwise until it turned back to the same base orientation (360, 0 degrees). The design day heating values exhibit minimal changes because sunlight is not a factor when calculating the coldest time of the year – which is always a time at night when the sun is not out. Alternatively, the district heating shows large variation where the desirable, smaller district heating loads result when the longer sides of the house are south facing due to passive solar heating. We ultimately found that the base design performed the best because the two longest sides of the home face north and south with south facing wall being the side with the largest glazing area.

6.2 Objective 2: Design, Build, and Test an Innovative Heating System

6.2.1 Peak Heating Load Profile

The graphs displaying the outdoor temperatures and solar irradiation values for our winter design day are shown in Figure 50 and Figure 51 respectively.

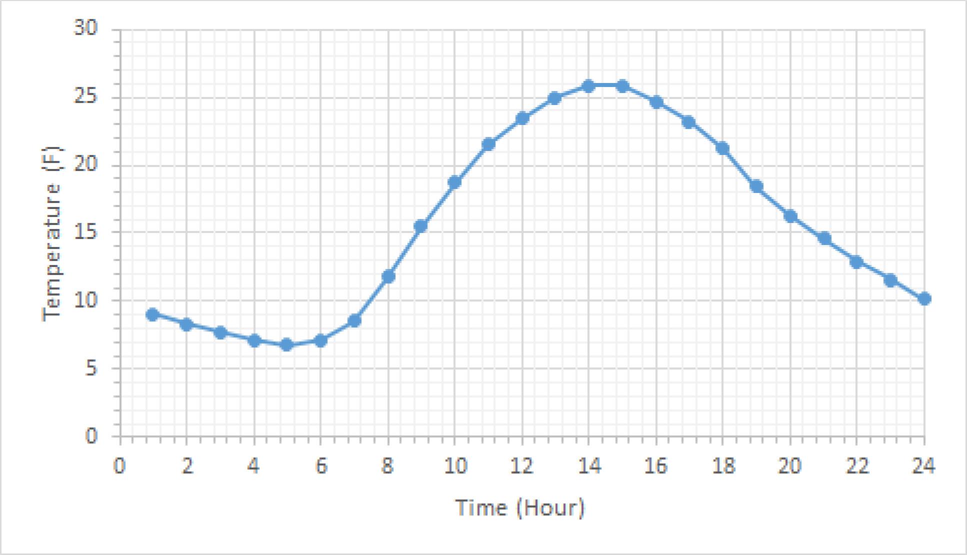


Figure 50: Winter Design Day, Hourly Outdoor Temperatures

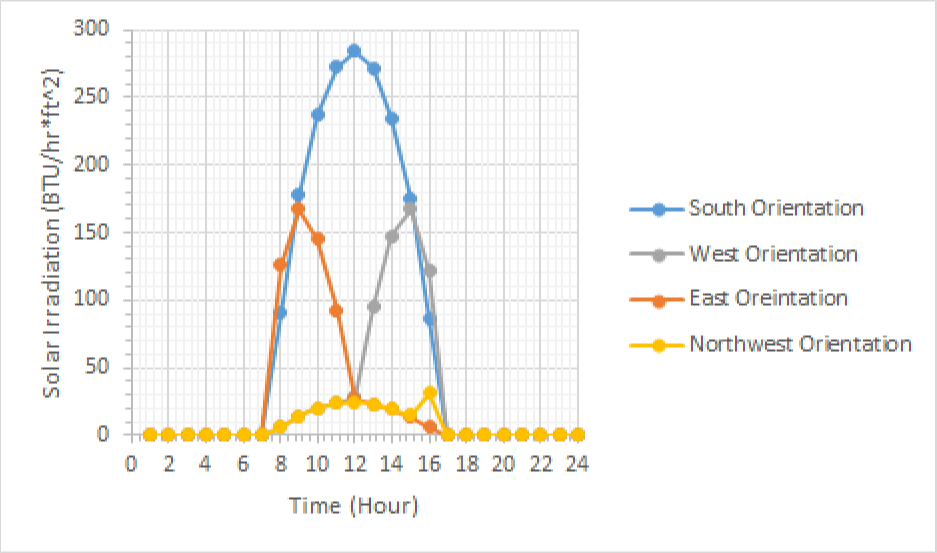


Figure 51: Winter Design Day, Solar Irradiation Values

From Figure 51 we found that the times of the day where we needed to calculate the heating load were hours 1 through 8 and hours 17 through 24. We checked these time frames with the time frames for zero irradiation for the months of December and February displayed in Figure 52.

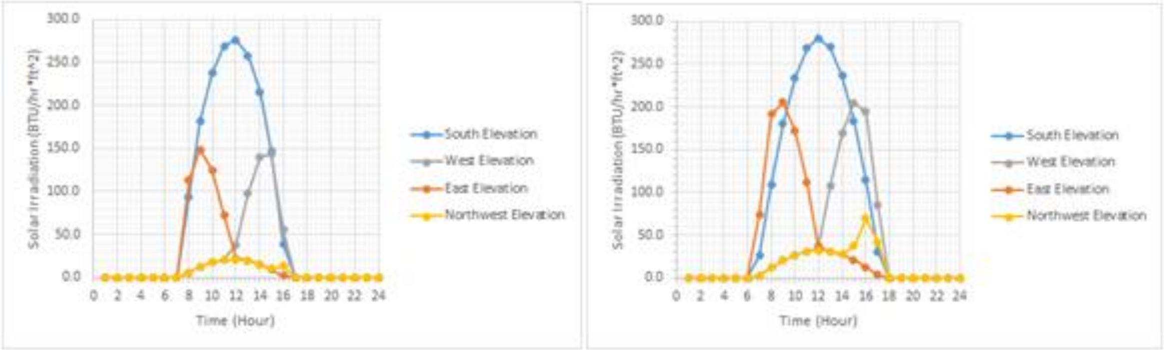


Figure 52: Solar Irradiation Values for December (Left) and February (Right)

Because the time frames for zero irradiation for both of these months included no new hours and all of the hours found for the month of January, we used hours 1 through 8 and hours 17 through 24 as well as the outdoor temperatures for the month of January, from Figure 50, to conduct the heating load calculations.

Manual Heat Load Calculations

After solving the 14 equations presented in Appendix B using the method described in the Methodology chapter, we obtained the following graph depicting the heat gain, infiltration heat loss, convection heat loss, and radiation heat gain for the hours in our heating load profile.

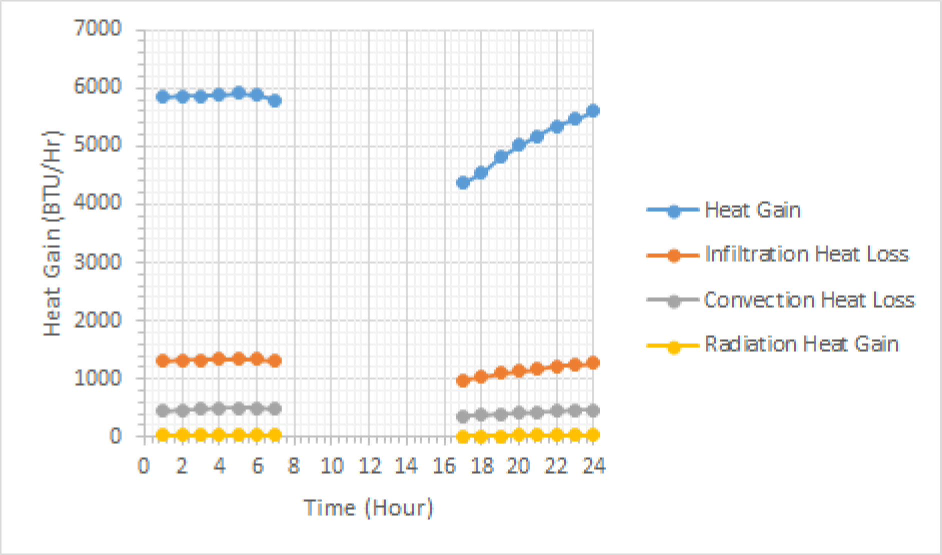
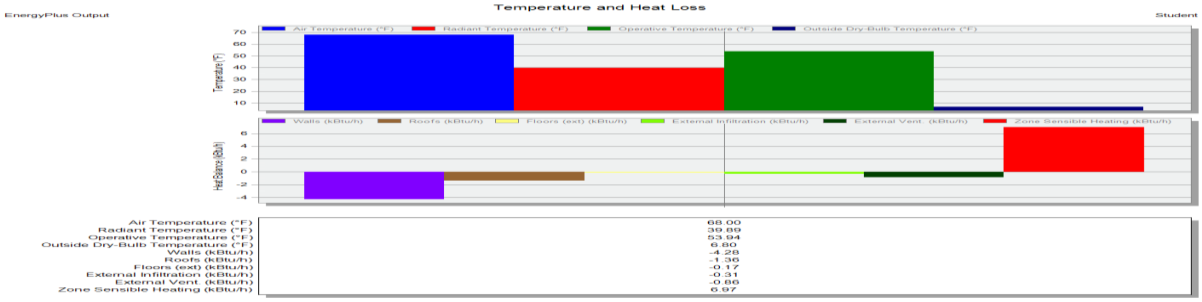


Figure 53: Winter Design Day, Trailer Heat Gains and Losses

The experimental data shows minimal radiation gain, whereas the losses due to air infiltration are large. However, it was found that the maximum amount of heat needed to heat the space to a set point temperature of 68 °F occurs at hour 5, at a value of 5,919.77 Btu/hr. Therefore, we can deduce that we will need a heat pump that can supply at least 6 kBtu/hr.

DesignBuilder Heat Load Calculations

From the data that we imputed into the DesignBuilder model of the trail alone with Worcester's weather data DesignBuilder produced the following heat balance breakdown.



Air Temperature (°F)	68.00
Radiant Temperature (°F)	39.89
Operative Temperature (°F)	53.94
Outside Dry-Bulb Temperature (°F)	6.80
Walls (kBtu/h)	-4.28
Roofs (kBtu/h)	-1.36
Floors (ext) (kBtu/h)	-0.17
External Infiltration (kBtu/h)	-0.31
External Vent. (kBtu/h)	-0.86
Zone Sensible Heating (kBtu/h)	6.97

Figure 54: DesignBuilder, Trailer Heat Gains and Losses

In Figure 54 the heat balance is shown in the second graph where the purple, brown, yellow, neon green, and dark green bars represent the heat loss from the walls, roof, floor, external infiltration, and external ventilation respectively. The software determined that in order to maintain the trailer at the requested set point temperature of 68°F, the heat pump must supply 6.97 kBtu/hr.

This result was about 15% larger than the value obtained from our hand calculations, but in order to ensure that we would be able to heat the trailer, we decided to use the maximum heating load value calculated when selecting our heat pump.

6.2.2 Equipment Sizing

The following table presents the equipment sizes as we calculated using the equations presented in the Methodology Chapter.

Table 4: Material and Equipment Sizing

Material/Equipment	Quantity	Size
Solar Collector	1	~53 ft^2 (30 tubes)
Heat Pump	1	16 kBTU/hr
Storage Drums	4	55 gallons each
Wilo Star Pump	2	6.67 GPM
March Pump	1	8.5 GPM
Expansion Tanks	2	Solar loop: 4.7 gallons Heating loop: 14 gallons
Piping		Solar loop: ¾” flexible steel Heating loop: ¾” PEX
Pressure Relief Valve	1	-
Air Relief Valve	2	-
Ball Valve	2	-
Check Valve	1	-
Three-Way Motorized Valve	1	-
Temperature Sensors	8	-
Insulation	8	4’x8’x2” R-31 rigid board insulation
Fluids	2	Solar loop: 50/50 water/glycol mix Heating loop: 75/25 water/glycol mix

6.2.3 Creating a Mathematical Model

The original graph that we obtained that was based on the system that we built with one 50 square foot solar collector and four 55 gallon storage drums is displayed in Figure 55.

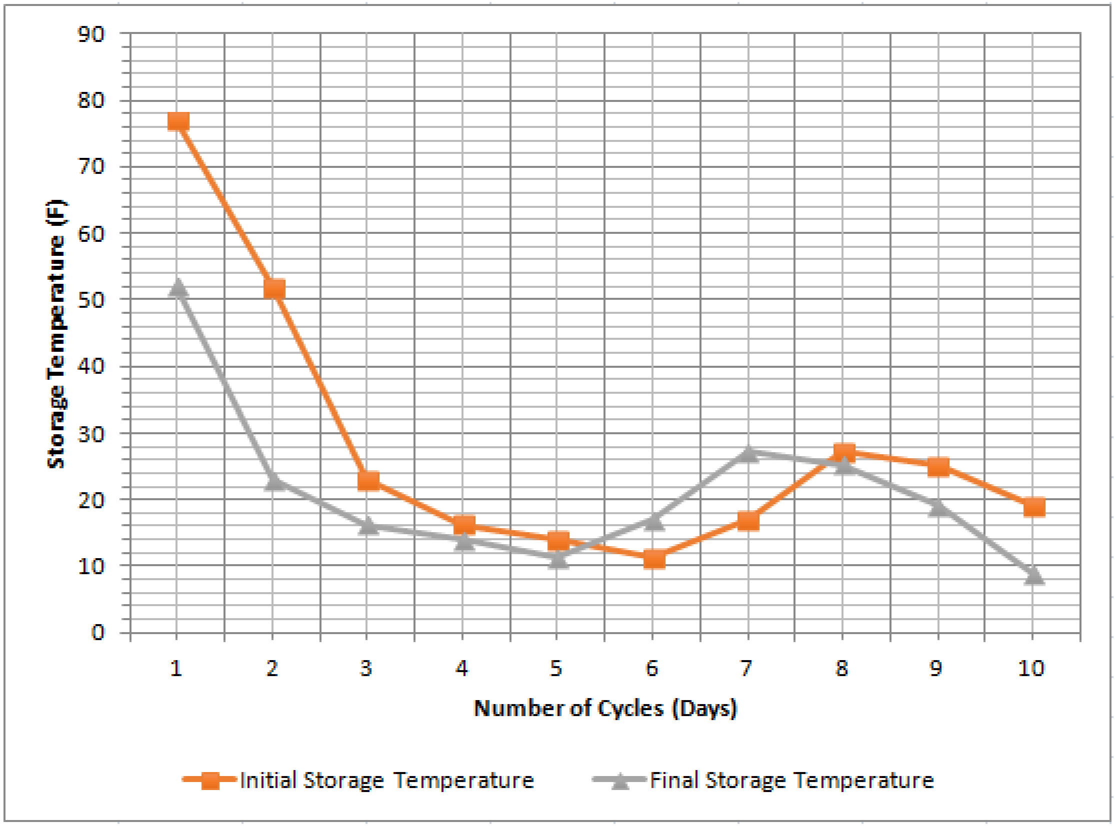


Figure 55: Daily Storage Temperatures for As Built System

From the graph we can see that the temperature within the storage drums dropped rather quickly and maintained temperatures below 30°F, which although is above the freezing point of the water and glycol mixture, it is not optimal for providing temperatures for heating the space. From Figure 56 however, we can see that the system is operating as expected over the course of a day where the temperature within the drums continuously decreases when the sun is not present and steadily increases when it is.

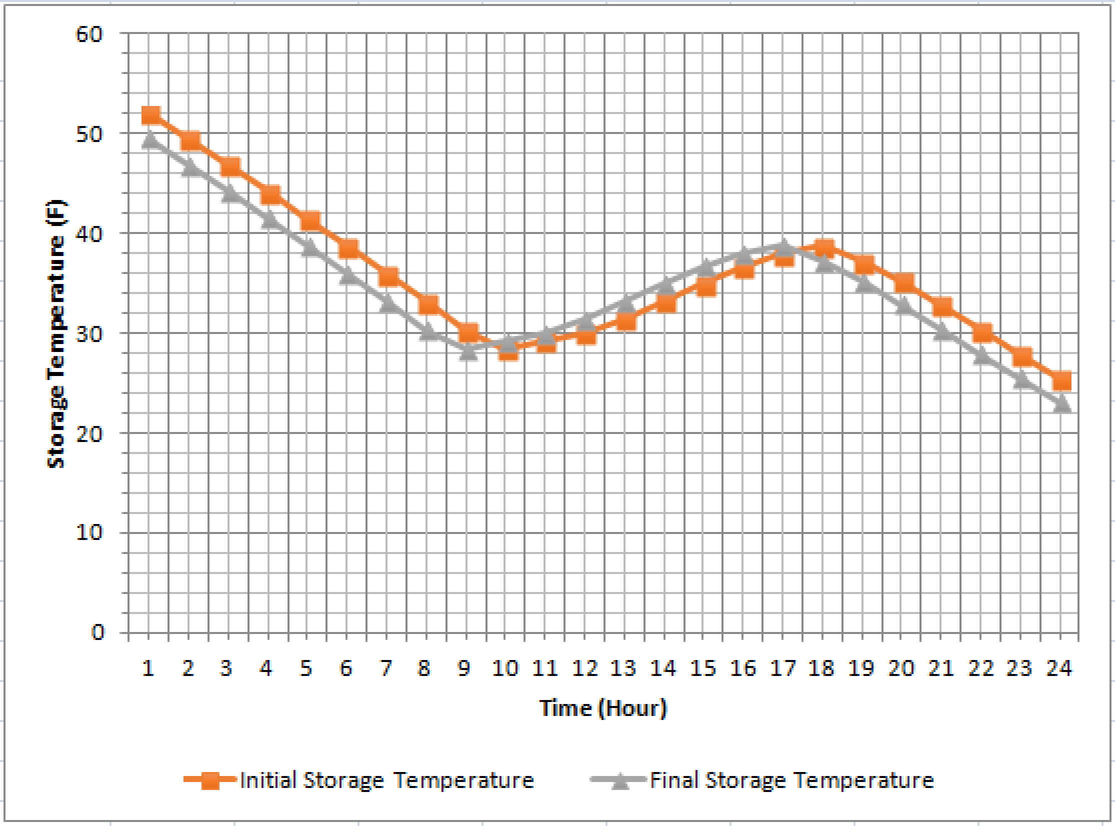


Figure 56: Hourly Storage Temperatures for As Built System

Although the temperature within the tanks is not within the desired range, which would be above the set point temperature, this suggests that the system is simply not sized correctly.

After making adjustments to both the collector area and the storage volume we found that the only combination to maintain the storage temperature above 40^{o}F was a collector area equivalent to two of the collectors that we purchased and a storage volume equal to our current volume provided by four 55 gallon drums.

6.2.4 System Design and Construction

Although the system design and construction was carried out rather smoothly, in accordance with the experimental set up described in Chapter 4.0, we were not able to implement a fully functioning system. Our inability to fill the system and have it maintain pressure, in addition to not being able to incorporate our control schematic, prevented us from gathering results on the system's functionality.

6.2.5 Electrical Design and Controls

The electrical components and their associated electrical requirements for our system are presented in Table 5**Error! Reference source not found.**.

Table 5: Summary of Electrical Components

Pump Name	Description	Voltage (V)	Amperage (A)	Frequency (Hz)	Power (W)
SunRain Mini Solar Pump Station (Solar Pump 1 & 2)	Wilo Star RS15/6 Sanitary Pump	115	0.9	60	103.5
March Pump	Magnetic Drive Pump, LC-3CP-MD	115	0.324	50/60	37.285
Marine Heat Pump	Marine Heat Pump, MSB16K2	110-120	RC: 10.8. SC: 17.6[a]	60	1480[b]
Three-Way Motorized Valve	Honeywell, V8044A1044	24	0.32	60	6/5

[a] RC: Running Current, SC: Starting Current
[b] Maximum input consumption

When considering these four components we determined that our system required a circuit that could handle a starting current of 20.044 A and a running current of 13.244 A. Therefore, the pumps were all placed on one circuit, with a circuit breaker rated at 20 A, at a voltage of 120 V. In general, a 20 A circuit trips at about 80 percent of the rating. In other words, the circuit breaker can only carry 16-A on a continuous basis. Therefore, to avoid this overload, we will turn on each pump one at a time when powering up the system; this method essentially delivers small amounts of amperages to the circuit in time intervals, rather than supplying the circuit with the full load amperage of every pump.

Our pump schedule can be seen in

Table 6.

Table 6: Pump Schedule

	Wilo Star Pump (solar)	**Wilo Star Pump (heating)**	**March Pump**	**Marine Heat Pump**	**Three-Way Motorized Valve**[a]
Charging	ON	ON	OFF	OFF	B
Heating (Day Cycle)	ON	ON	ON	ON	A
Heating (Night Cycle)	OFF	ON	ON	ON	A
Off	OFF	OFF	OFF	OFF	-

We determined that our system will have four operating. In charging mode, both of the Wilo Star pumps will be on in order to circulate the fluid within the solar loop and within the drums in the heating loop. Additionally, the motorized valve will be in position as to stop the flow to the heat pump which eliminates the need for the heat pump and march pump to be turned on. In heating mode during the day all of the pumps will be turned on and the motorized valve will allow flow to the heat pump, this will allow the system to heat the trailer while still collecting heat from the sun. In heating mode during the night, the Wilo Star pump for the solar loop will be turned off as to eliminate the possibility of re-radiating the stored heat into the outside air. The Wilo Star pump for the heating loop as well as the march and marine heat pump will remain on as the fluid will flow through the heat pump in order to heat the trailer. The final mode is the off mode where all of the pumps are off and the system is not functional.

When fully integrated into the system, the pump schedule should be controlled based on the time of day and the trailer set point temperature. This would cause the system to function in charging mode when the trailer temperature is greater than the set point temperature and the hour is between hour 8 and 17. The system would function in day heating mode when the temperature in the trailer is below the set point temperature and the hour is between 8 and 17. Finally, night heating mode would be enabled when the temperature in the trailer is below the set point temperature and the hour is not between 8 and 17.

To accomplish this system control, our proposed control schematic is presented in Figure 57. Additionally, Appendix C presents a pump control flow chart that describes the function of our proposed system control schematic.

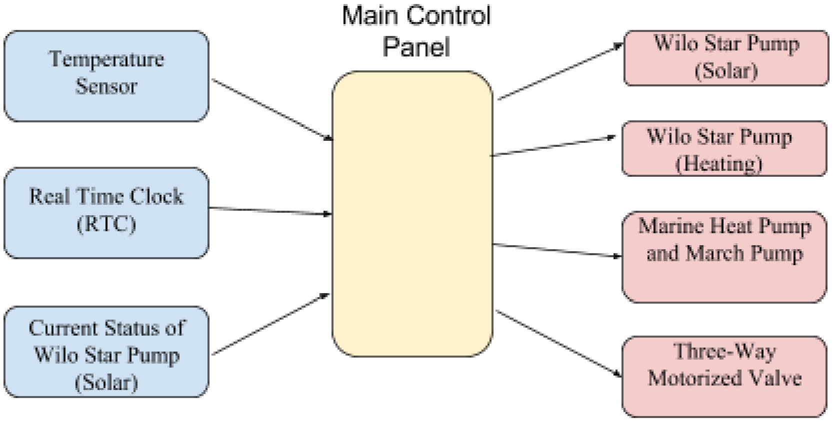


Figure 57: Proposed Control Schematic

The design requires temperature, time, and current solar loop pump status to be input parameters that indicate to the main control panel whether to turn the pumps on or off and which way to switch the motorized valve. Because the four pumps are connected on the same circuit, a means of integrating both power and control to the pumps needs to be considered to allow for proper function of the system.

6.3 Objective 3: Feasibility of Unity Home Integration

In order to integrate our system model into the model of the Xyla platform we needed to enter the overall efficiency of our system. However, due to the lack of information on our heat exchanger we were unable to successfully integrate our system with the Xyla platform.

Using our mathematical model we found that, same as our trailer, two solar collectors and four storage drums would be necessary to heat the Xyla house. Figure 58 presents the initial and final storage temperature over the same ten day period in January.

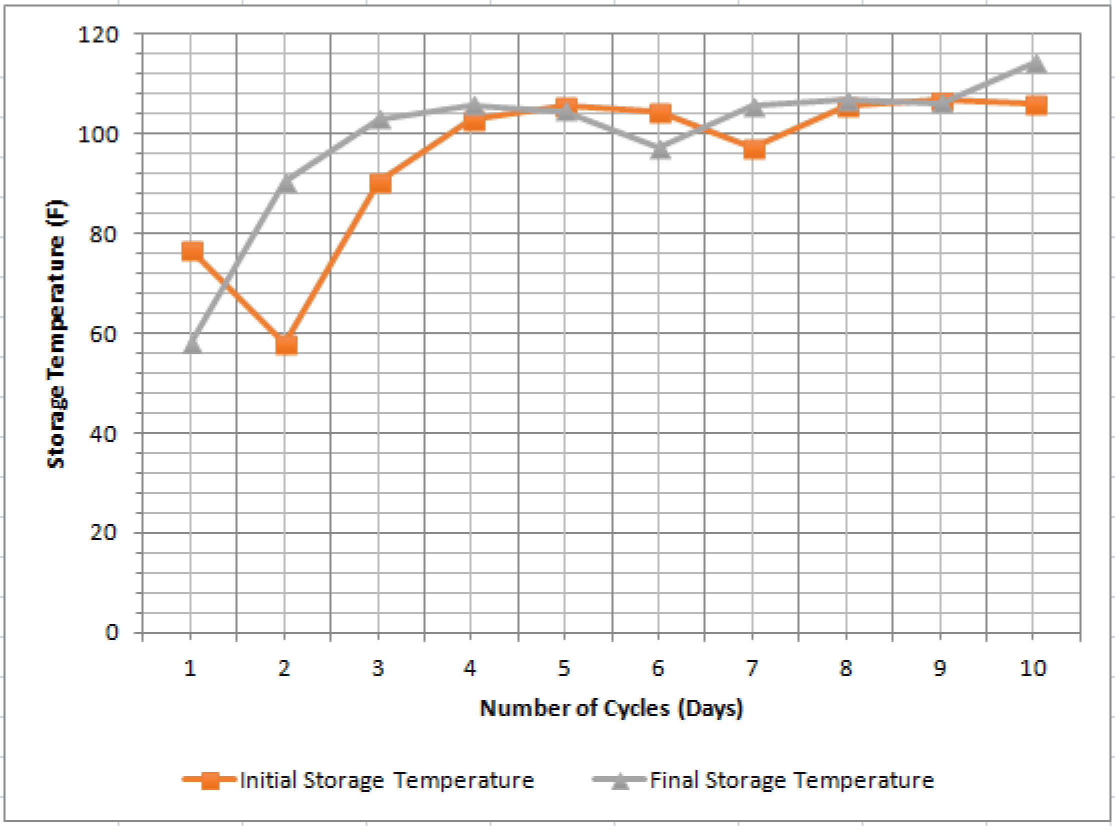


Figure 58: Daily Storage Temperatures for Xyla Platform

The graph has an upward trend that seems to level off around 100°F; additionally, when looking at the hourly temperatures throughout the ten day period, the storage temperature never falls below 40°F.

6.4 Objective 4: Develop a Set of Strategies and Recommendations

Passive Changes for Unity Homes

We recommend that Unity Homes continues to use their current design and construction methods. Based on our energy modeling we found that the current window type, insulation, and orientation of Unity Home's houses provides the most efficient and cost effective solution.

Future Work on Solar Water Heating System

We recommend that a future project be developed to further extend and integrate a controls set up for our system. The control schematic, pump schedule, and pump control flow chart that we created should help guide future work as they collectively describe how our system is intended to operate. In addition to the automatic control of the pumps and motorized valve, the temperature sensors attached along the piping and the sides of the drums of the heating loop should be connected to the RESOL controller, or an alternative source, in order to automatically collect temperature at specified time intervals. A proper controls set-up to accomplish these two tasks will allow our system to function seamlessly and without manual operation.

We recommend that a future project be developed to continue our work on creating an operable system. Further investigation is needed to determine why the solar loop is not able to maintain pressure. Once a conclusion is reached and the necessary steps are taken to solve the problem, filling of the heating loop can commence. Successful filling of both loops will allow the system to be turned on and data collection can begin.

We recommend that a future project be developed to modify our system to allow for space cooling and domestic hot water use. The marine heat pump that we purchased has the ability to operate in cooling mode. Modifying our system to include space cooling would increase its usefulness as it would be able to function as a modern HVAC system currently does. When conducting research for building our system we found that similar systems to ours had been developed to provide hot water to homes. Thus, we believe that the integration of domestic hot water into our system is possible and we believe that a final version of our system that includes heating, cooling and domestic hot water is a system that Unity Homes is looking to integrate into their homes.

Unity Homes Integration

We recommend that further investigation be made to obtain a system efficiency value. In order to successfully integrate our system model into the Xyla platform and overall efficiency value needs to be calculated. This calculation can only be made once results are obtained from either a mathematical model or experimental testing. If a model will be used, further work to develop the mathematical model that we presented in this paper is necessary to accurately represent our system. Alternatively, a new model could be used or newly developed to satisfy our system parameters.

We recommend that serious consideration be taken to determine the feasibly of integrating our system into a Unity Homes house. Because our system requires a large amount of space, thought needs to be given as to where the system will be located. Depending on the number of solar collectors and storage drums necessary the drums may be able to be located inside the home, possibly in the basement. Additionally, thought must be given to the appearance of the system and whether or not a roof mounted solar collector will be favorable over a ground mounted system.

We recommend that a cost analysis be performed to compare our systems costs with the cost of the HVAC system already used within a Unity Home. Taking into account both the initial cost of the system as well as the cost savings allowed by the elimination of electric or gas consumption a cost analysis can be performed. This analysis will further illustrate the feasibility of the integration of our system. Additionally, calculations and an associated cost analysis can be performed for our system with the addition of using solar panels as a means to power our system. This addition to our system would not only provide potential long term cost savings, it would also create an HVAC system to help in achieving a net zero energy house design.

Conclusions

The goal of our project was to improve Unity Home's home design by investigating both passive and active methods. We conducted research, performed energy modeling analyses, and built a solar water heating system to formulate recommendations for Unity Homes and future WPI students. Our research assisted us in choosing variables to consider when attempting to passively improve Unity Home's design. The energy modeling that we performed to accomplish this allowed us to conclude that Unity Home's current design and construction techniques are the most efficient and cost effective. When considering active improvements we were able to conclude that our system would need to include an additional solar collector in order to effectively heat either the trailer or the Xyla house. We were also able to formulate many recommendations to assist future WPI project teams that continue our work as they outline our intentions for successfully completing of our work as well as additional topics to investigate upon obtaining further results.

References

(2015). Retrieved from http://scienceline.ucsb.edu/getkey.php?key=1464: UCSB ScienceLine.

A Better Way to Build. (n.d.). Retrieved from http://unityhomes.com/: Unity Homes.

Active Solar Systems. (n.d.). Retrieved from http://www.usc.edu/dept-00/dept/architecture/mbs/tools/thermal/controls_activesolar.html.

Active System. (n.d.). www.engineering-dictionary.org/ACTIVE_SYSTEM.

Bainbridge, D. A. (2005). A Water Wall Solar Design Manual. Retrieved from http://www.builditsolar.com/Projects/SpaceHeating/AWaterWallIntro.pdf.

Building a Better Trombe Wall. (n.d.). Retrieved from http://www.nrel.gov/docs/legosti/fy98/22834.pdf: NREL.

Congress, U. S. (2007). *Energy Independence and Security Act of 2007*. Washington, DC.

Daylighting. (n.d.). Retrieved from https://energy.gov/energysaver/daylighting: energy.gov.

de Gracia L.F. Cabeza, A. (2015). *Phase Change Materials and Thermal Energy Storage for Buildings*. https://beopt.nrel.gov/sites/beopt.nrel.gov/files/Alvaro%20&%20Garcia,%202015%20-%20Phase%20change%20materials%20and%20thermal%20energy%20storage%20for%20buildings.pdf.

Dimock, L. (2013). Your Home Electrical System. Retrieved from http://www.thecircuitdetective.com/bkgrd.htm.

Domestic Solar Water Heating Installation Manual. (n.d.). Northern Lights.

Evacuated Tube Collector. (2017). Retrieved from http://www.alternative-energy-tutorials.com/solar-hot-water/evacuated-tube-collector.html: Alternative Energy Tutuorials.

Fallahi, A. (2016). Load Calculations and Principles-Quasi-Steady-State.

Geothermal Heating and Cooling. (n.d.). Retrieved from http://groundsourcewi.com/geothermal: Ground Source.

Harris, C. (1991). U.S.A Patent No. https://www.google.com/patents/US4993483.

International Living Future Institute. (2017). Net Zero Energy Building. Retrieved from https://living-future.org/net-zero/.

Jafarkazemi, F., & Abdi, H. (2012). Evacuated Tube Solar Heat Pipe Collector Model and Associated Tests. *Journal of Renewable and Sustainable Energy, 4*(023101).

Jones, B. (2013). Flat Plate Solar Thermal Collectors: Overview. Retrieved from http://thegreenhome.co.uk/heating-renewables/solar-panels/flat-plate-solar-thermal-collectors-overview/: The Green Home Construction & Lifestyle.

Kulkami, G. N., Kedare, S. B., & Bandyopadhyay, S. (2006). Determination of Design Space and Optimization of Solar Water Heating Systems. *Solar Energy, 81*(8), 958-968.

McNabb, N. (2013). Strategies to Achieve Net-Zero Energy Homes: A Framework for Future Guidelines. Retrieved from http://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1140.pdf: National Institute of Standards and Technology.

Measuring Solar Thermal Energy. (2012). Retrieved from http://www.home-energy-metering.com/solar-thermal-energy.html: UtilEcon Services, LLC.

Meyers, R. J., Williams, E. D., & Matthews, H. S. (2010). *Scoping the Potential of Monitoring and Control Technologies to Reduce Energy use in Homes*. Paper presented at the Energy and Buildings.

Passive House Certification Criteria. (n.d.). Retrieved from https://passivehouse-international.org/index.php?page_id=150: International Passive House Association.

Reardon, C. (n.d.). Thermal Mass. Retrieved from http://www.yourhome.gov.au/passive-design/thermal-mass: Australian Government.

Sedra, A. S., & Smith, K. C. (2014). *Microelectronic Circuits* (7th edition ed.): Oxford University Press.

Solar Geyser Technology Explained. (n.d.). Retrieved from http://www.solarsense.co.za/solar-water-heating-explained.php: Solar Sense Solar Heating Specialists.

Solar Photovoltaic Technology Basics. (n.d.). Retrieved from https://www.nrel.gov/workingwithus/re-photovoltaics.html: NREL.

Solar Pool Heating. (n.d.). Retrieved from http://www.alternative-energy-tutorials.com/solar-hot-water/solar-pool-heating.html: Alternative Energy Tutorials.

Solar PV Technology. (n.d.). Retrieved from http://www.altenergy.org/renewables/solar/solartechnolgy.html: Alternative Energy.

Solar Thermal Water Heating. (n.d.). Retrieved from http://www.powellrangesolutions.co.uk/services/solar/: Powell Range Solutions.

This is LEED: Better Buildings are our Legacy. (n.d.). Retrieved from http://leed.usgbc.org/leed.html?gclid=Cj0KEQjw6uO-BRDbzujwtuzAzfkBEiQAAnhJ0Osm_unfbmKTiWoELSqAC_EiGMMngXtfToe5yzS8disaApr08P8HAQ: U.S. Green Building Council.

Types of Insulation. (n.d.). Retrieved from https://energy.gov/energysaver/types-insulation: energy.gov.

Understanding Your Home Electrical System. (2015). Retrieved from http://www.esfi.org/resource/understanding-your-home-electrical-system-213: Electrical Safety Foundation International.

Window Types. (n.d.). Retrieved from https://energy.gov/energysaver/window-types: energy.gov.

Appendix A: Nomenclature

Variable	Description	Equation	Value	Units
Peak Heating Load Profile				
$A_{E,wall}$	Area of east wall	$W \times H = 5.75 \times 6.833$	39.291	ft^2
$A_{NW,wall}$	Area of northwest wall	$L \times H = 12 \times 6.833$	82.000	ft^2
$A_{S,wall}$	Area of south wall	$L \times H = 12 \times 6.833$	82.000	ft^2
$A_{W,wall}$	Area of west wall	$W \times H = 5.75 \times 6.833$	39.291	ft^2
A_{floor}	Area of floor slab	$L \times W = 12 \times 5.75$	69.000	ft^2
A_{roof}	Area of roof	$L \times W = 12 \times 5.75$	69.000	ft^2
ACH	Air changes per hour	-	0.600	ACH
α_{wall}	Solar absorptivity of the wall	-	0.300	-
C_p	Specific heat of air	-	0.240	$Btu/_{lb_m}\ {}^\circ F$
ε	Emissivity	-	0.95	-
$F_{a,wall}$	Heat transfer view factor from surface to surface	-	**Varies**	-
$F_{s\text{-}sky}$	Heat transfer view factor from the sky	-	0.9	-
h_i	Convective heat transfer coefficient for the interior of the wall	-	0.560	$Btu/_{hr}\,ft^2\,{}^oF$
$h_{i,floor}$	Convective heat transfer coefficient for the interior portion of the floor	-	0.730	$Btu/_{hr}\,ft^2\,{}^oF$
$h_{i,roof}$	Convective heat transfer coefficient for the interior portion of the floor	-	0.180	$Btu/_{hr}\,ft^2\,{}^oF$
h_o	Convective heat transfer coefficient for the exterior of the wall	$((C_t(\Delta t)^{\frac{1}{3}})^2 + (aV^b)^2)^{\frac{1}{2}}$	2.276	$Btu/_{hr}\,ft^2\,{}^oF$

$h_{r,sky,v}$	Long wave radiation coefficient from the sky	$\varepsilon\sigma(\frac{F_{s-sky}\left(F_{sky}^4 - T_{s,e}^4\right)}{T_{sky}T_{s,e}})$	**Varies**	$Btu/_{hr}\, ft^{2\ o}F$
$h_{r,wall,s,nw}$	Long wave radiation coefficient from the south and northwest wall	$4F_{a,wall}F_E\sigma T_{avg}^3$ $(F_{a,wall} = .298)$	0.2694	$Btu/_{hr}\, ft^{2\ o}F$
$h_{r,wall,w,e}$	Long wave radiation coefficient from the west and east wall	$4F_{a,wall}F_E\sigma T_{avg}^3$ $(F_{a,wall} = .125)$	0.1130	$Btu/_{hr}\, ft^{2\ o}F$
$h_{r,floor}$	Long wave radiation coefficient from the roof	$4F_{a,wall}F_E\sigma T_{avg}^3$ $(F_{a,wall} = .224)$	0.2025	$Btu/_{hr}\, ft^{2\ o}F$
$h_{r,roof}$	Long wave radiation coefficient from the roof	$4F_{a,wall}F_E\sigma T_{avg}^3$ $(F_{a,wall} = .224)$	0.2025	$Btu/_{hr}\, ft^{2\ o}F$
m_{air}	Mass flow rate of air	$\rho_{air}V_{room}ACH$	22.066	$lb_m/_{hr}$
ρ_{air}	Density of air	-	0.0780	$lb_m/_{ft^3}$
$q_{intGain}$	Internal heat gain	-	0	$Btu/_{hr}$
σ	Stefan Boltzmann constant	-	0.1714e-8	$Btu/_{hr}\, ft^2R^4$
T_{avg}	Average room Temperature	-	**Varies**	°F
T_o	Outside temperature	-	**Varies**	°F
T_{sky}	Sky temperature in the winter	T_o - 10.8	**Varies**	°F
$T_{sky,v}$	Sky temperature for vertical surfaces in the winter	$\left(\cos\left(\frac{\alpha}{2}\right)\right)T_{sky} + (1 - \cos\left(\frac{\alpha}{2}\right))T_o$	**Varies**	°F
T_r	Temperature inside the trailer in the winter	-	68	°F
U_{wall}	Heat loss coefficient of walls	-	0.5606	$Btu/_{hr}\, ft^{2\ o}F$
U_{floor}	Heat loss coefficient of floor	-	0.5606	$Btu/_{hr}\, ft^{2\ o}F$

U_{roof}	Heat loss coefficient of roof	-	0.5606	$^{Btu}/_{hr}\, ft^{2}\, {}^{o}F$
V_{room}	Volume of room	$L \times W \times H$	471.50	ft^3
Circulating Pumps				
c	Hazen-Williams roughness constant	-	140	-
d_h	Inside hydraulic diameter	$d_h = 4\, ^{A}/_{p}$	.75	in
q	Volume flow rate	-	1.5	gal/min
Expansion Tanks				
P_f	Minimum operating pressure at the tank	-	30	$psig$
P_o	Maximum operating pressure at the tank	-	52.4	$psig$
t	Maximum average design temperature	-	180	°F
V_g	Total system water content	-	220	gal
Creating a Mathematical Model				
A_c	Area of the solar collector	-	52.8	ft^2
A_{st}	Surface area of storage drums	$4(2\pi rh + 2\pi r^2)$	95.9	ft^2
C_p	Specific heat of working fluid	-	.997	$^{Btu}/_{lb_m}\, {}^{\circ}F$
F_R	Collector heat removal factor	-	.554	-
G_T	Solar irradiation	-	**Varies**	$^{Btu}/_{hr}\, ft^{2}$
I_T	Solar radiation intensity	-	**Varies**	$^{Btu}/_{hr}\, ft^{2}$
$\dot{m}_L$	Desired load mass flow rate	-	9.6	$^{ft^3}/_{hr}$
ρ	Density of working fluid	-	61.99	$^{lb_m}/_{ft^3}$

q_{Ls}	Load met by solar energy	-	**Varies**	Btu/hr
q_s	Solar useful heat gain	-	**Varies**	Btu/hr
q_{stl}	Rate of storage loss	-	**Varies**	Btu/hr
t	Time step	-	1	hr
T_a	Ambient temperature	-	68	°F
T_L	Desired load temperature	-	90	°F
T_R	Make up fluid temperature	-	77/180	°F
T_{st}	Storage temperature	-	**Varies**	°F
T_{stf}	Storage temperature at end of time step	-	**Varies**	°F
T_{sti}	Storage temperature at beginning of time step	-	**Varies**	°F
$\tau\alpha$	Average transmittance absorptance product	-	1	-
U_L	Collector overall heat loss coefficient	-	.8	$Btu/hr\,ft^2\,{}^oF$
U_{st}	Storage heat loss coefficient	-	.05	$Btu/hr\,ft^2\,{}^oF$
V_{st}	Storage volume	$4(\pi r^2 h)$	29.41	ft^3

Appendix B: Heat Balance Equations for Design Space Heating

South Wall

Outer face:

$(U_{wall} + h_o + h_{r,sky,v})\mathbf{T}_{s1} - U_{wall}\mathbf{T}_{s2} = h_oT_o + h_{r,sky,v}T_{sky,v}$

Inner face:

$U_{wall}\mathbf{T}_{s1} - (U_{wall} + h_i + h_{r,wall,s,nw})\mathbf{T}_{s2} + h_{r,wall,s,nw}\,\mathbf{T}_{avg} = -h_iT_r$

West Wall

Outer face:

$(U_{wall} + h_o + h_{r,sky,v})\mathbf{T}_{s3} - U_{wall}\mathbf{T}_{s4} = h_oT_o + h_{r,sky,v}T_{sky,v}$

Inner face:

$U_{wall}\mathbf{T}_{s3} - (U_{wall} + h_i + h_{r,wall,w,e})\mathbf{T}_{s4} + h_{r,wall,w,e}\,\mathbf{T}_{avg} = -h_iT_r$

Northwest Wall

Outer face:

$(U_{wall} + h_o + h_{r,sky,v})\mathbf{T}_{s5} - U_{wall}\mathbf{T}_{s6} = h_oT_o + h_{r,sky,v}T_{sky,v}$

Inner face:

$U_{wall}\mathbf{T}_{s5} - (U_{wall} + h_i + h_{r,wall,s,nw})\mathbf{T}_{s6} + h_{r,wall,s,nw}\,\mathbf{T}_{avg} = -h_iT_r$

East Wall

Outer face:

$(U_{wall} + h_o + h_{r,sky,v})\mathbf{T}_{s7} - U_{wall}\mathbf{T}_{s8} = h_oT_o + h_{r,sky,v}T_{sky,v}$

Inner face:

$U_{wall}\mathbf{T}_{s7} - (U_{wall} + h_i + h_{r,wall,s,e})\mathbf{T}_{s8} + h_{r,wall,s,e}\,\mathbf{T}_{avg} = -h_iT_r$

Roof

Outer face:

$(U_{roof} + h_o + h_{r,sky,v})\mathbf{T}_{roof1} - U_{roof}\mathbf{T}_{roof2} = h_oT_o + h_{r,sky,v}T_{sky,v}$

Inner face:

$U_{roof}\mathbf{T}_{roof1} - (U_{roof} + h_{i,roof} + h_{r,roofl})\mathbf{T}_{roof2} + h_{r,roof}\,\mathbf{T}_{av\,g} = -h_{i,floor}T_r$

Floor

Outer face:

$(U_{floor} + h_o + h_{r,sky,v})\mathbf{T}_{floor1} - U_{roof}\mathbf{T}_{floor2} = h_oT_o + h_{r,sky,v}T_{sky,v}$

Inner face:

$U_{floor}\mathbf{T}_{floor1} - (U_{floor} + h_{i,floor} + h_{r,floor})\mathbf{T}_{floor2} + h_{r,floor}\,\mathbf{T}_{avg} = -h_{i,floor}T_r$

Area-Average Temperature

$A_{S,wall}\mathbf{T}_{s2} + A_{W,wall}\mathbf{T}_{s4} + A_{NW,wall}\mathbf{T}_{s6} + A_{E,wall}\mathbf{T}_{s8} + A_{roof}\mathbf{T}_{roof2} + A_{floor}\mathbf{T}_{floor2} - \mathbf{T}_{avg}(A_{S,wall} + A_{W.wall} + A_{NW,wall} + A_{E,wall} + A_{roof} + A_{floor}) = 0$

Room-Air Node

$h_i(A_{S,wall}\mathbf{T}_{s2} + A_{W.wall}\mathbf{T}_{s4} + A_{NW,wall}\mathbf{T}_{s6} + A_{E,wall}\mathbf{T}_{s8}) + h_{i,roof}A_{roof}\mathbf{T}_{roof2} + h_{i,floor}A_{floor}\mathbf{T}_{floor2} + \mathbf{q}_{HVAC} = -m_{air}C_p(T_o - T_r) - q_{intGain} + h_i(A_{S,wall} + A_{W.wall} + A_{NW,wall} + A_{E,wall})T_r + h_{i,roof}A_{roof}T_r + h_{i,floor}A_{floor}T_r$

Appendix C: Pump Control Flow Chart