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Applications of Passive Solar Energy and Reclaimed Heat from Livestock Manure Decomposition

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Abstract

One energy intensive part of raising livestock in colder climates is keeping water warm and easily accessible to the animals in the winter. The objective of this project is to increase the sustainability of livestock farms by developing and implementing an energy conservation measure to decrease electric energy usage on the heating of water for livestock in the winter. One thing farmers have in excess is manure, an abundant and renewable resource for the farmers. This project will capitalize on that excess to encourage a creative use of resources often seen as waste, through implementing aspects of sustainability and conservation in the design of a compost heat recovery system to generate warm water by using the heat released in the breakdown of goat manure. The design uses concepts of passive solar energy in addition to the goat manure compost to warm water to a maximum temperature of 38 degrees Celsius. The design is also able to be modified into a more complex system for future improvement and mechanization. Theoretical work and system modeling in MATLAB has been completed to show the expected behavior of the designed system. Future studies should validate the system design through testing. Future testing will also allow for the collection of additional data to support more research and work in this area. A successful application of this design has the potential to save money for farmers as well as increasing the sustainability and energy independence of agriculture across the country and around the world.

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Executive Summary

This project aims to design and build a system that utilizes livestock manure to provide warm, fresh water access to livestock farms in the winter. The goals of the project consisted of two main parts: to first study the method of maximizing the heat released from decomposing manure and then determine the most efficient way to use that heat to warm water. The project scope was defined from here, with the expected deliverables of data and analysis of tested compost materials, multiple design concepts, a final design and MATLAB model, and an installation of the final system for design verification and modeling validation.

Phase 1 of the project started with building a test environment to analyze four different compost mixtures and determine which would reach the highest temperature during the decomposition process. The mixture reaching the highest temperatures and having the smallest temperature fluctuations was the human manure, goat manure, and hay mix. For Phase 2, the final design chosen incorporates passive solar energy and the decomposition of the manure in a stand-alone, simple compost heat recovery system. The seasonality of the project, with the system designed to be used in winter, led to time constraints that kept a completed full-scale system from being tested in operating conditions. Basic concept testing was conducted and modeling calculations and predictions were completed.

Significant work was done towards the full realization of a system to heat water for livestock applications. The original goal of the project was to install and test a full-scale system, but due to time constraints and a lack of funding resources only a final conceptual design and MATLAB model were completed. Future work will validate and test this design in real use applications. Most of the initial goals and objectives for the project were achieved, with the most significant of these being the completed MATLAB model of the final system and the research into possible applications of livestock manure.

As this work continues forward, significant steps will be taken towards building and testing of a full-scale system to validate the MATLAB model results. There will also be considerations of additional design features and increasing complexity of the model for more accuracy. If working on a project like this again, steps would be taken to better ensure the timing of the work lines up with the seasonality of testing and data collection.

Introduction

A. Background and Motivation

Small family farms account for 90% of all farms in the United States. Over half of these farms make a profit of less than $10,000 a year in agricultural sales, demonstrating the lack of realization of economic success for many small family farmers (United States Department of Agriculture 30). The profitability of farms is impacted by many different factors, including weather variability, fluctuations in market prices, and operating costs. Some of these issues are not under the control of farmers, but operating costs are something farmers can control to some extent. High operation costs due to electricity and power consumption can be decreased through energy conservation measures to yield an increased profit margin. In addition to benefiting profits, energy conservation measures decrease the carbon footprint of farms, improving their sustainability and decreasing their environmental impact.

One of the largest costs for livestock farms is heating water for livestock in the winter. Livestock drink a lot of water, with estimates of up to 19 kg a day for lactating goats (Hart). To keep water access available to animals throughout the winter, water must be heated and kept above freezing or water must be brought to the animals regularly throughout the day. Heating any amount of water takes a significant amount of energy: 4190 J of energy are needed to warm one kilogram of water 1 °C. At the quantities of water consumed by livestock, the amount of energy needed to keep water from freezing for just one day would be substantial. One such method of keeping water from freezing is using electric heated water buckets. However, unless the agricultural operation has on-site renewable energy generation, the electricity used to keep the water from freezing is being pulled from the grid and is adding up to expensive electric bills. To avoid this economic burden, farmers could bring water to their livestock regularly and continue to refill buckets for the animals. This is a large time commitment for farmers though, and spending time on this could detract from their profits in other places.

A solution is needed that saves livestock farmers time, energy, and money while decreasing the environmental impact of agriculture. One option is to look at manure as a possible answer to this problem: as long as livestock are eating they'll be producing manure. This makes manure an excellent renewable, abundant resource for farmers to

utilize in some way. As manure breaks down, it releases large amounts of thermal energy into the surrounding environment—if that energy could be captured or converted in some way, there is a lot of potential in using manure for water heating purposes or more.

To approach this problem as sustainably-minded as possible with as wide reaching application as possible, goat manure was selected as the manure to be studied. Goats are one of the most commonly kept animals around the world, making this research beneficial to people both inside and outside the United States. When compared to dairy cows, goats require less water and release 88% less methane into the atmosphere (Broucek 1484). As methane is a considerable contributor to global warming at a CO_2 equivalent global warming potential of 25 and water scarcity is becoming an issue around the world, goats are a much more environmentally friendly animal than cows. But despite the focal point of the research being on goat manure, the resulting system is predicted to be applicable to a wide range of animal manures, as the basic systems, modeling, and engineering theory is the same.

B. *Compost Heat Recovery Systems*

Compost heat recovery systems (CHRSs) are systems designed to harness the thermal energy released during aerobic composting as a renewable heat source. They have been used in various forms for over 2000 years, with some of the earliest applications being hotbeds in northern China to extend the growing season in cooler weather. Though there is a long history of use of CHRSs, most of the modern day work with them has been in a commercial or academic setting—there has been little scientific exploration of compost heat recovery systems. This leaves a large gap in peer-reviewed literature regarding the potential energy that can be captured from these systems (Smith et al. S11). Despite this lack of controlled research and data, there are countless successful applications of CHRSs in the commercial and academic settings mentioned before.

Three main stages make up the process to recover heat from compost degradation: heat production, heat capture, and heat utilization (Smith et al. S11-12) Looking at heat production first, there is an ultimate amount of energy available in the compost materials, or feedstocks; however, it is impossible to release all of this energy as compost does not combust and does not completely oxidize the compounds that make up the compost

materials. The amount of heat that can be actually be produced then depends on how much energy is in the compost feedstock, how much the feedstock can break down, how long the composting process happens, and the conditions under which the compost is breaking down. Therefore, it is critical to consider these multiple factors in not only the compost material selections but the compost process design as well.

To capture the heat from decomposing compost, there are three methods used (Smith et al. S12). The first of these is a direct use of the heat released, for use in a greenhouse or similar structure. Second, conduction heat transfer is utilized through hydronic heating with in-pile heat exchangers—these systems are generally used when heated water is the goal of the system. The third method is a more modern approach, using the latent heat in the compost vapor in a condensing heat exchanger. This method captures the most heat from the compost, making it the most commonly used system for commercial CHRSs.

As stated previously, little peer-reviewed literature exists for these systems; however, there is still a large collection of academic papers and commercial examples that can be reviewed for an idea of the results one would expect from varying compost heat recovery systems. One such system is a single 1 m^3 bin used in conjunction with agricultural manures, developed by Niels Vemmelund and Leif Berthelsen of Jordbrugsteknisk Institut in 1979 (Smith et al. S14). This system was used to warm water, reaching a temperature of 40 °C with an energy generation rate of 2304 kJ/hr (Vemmelund and Berthelsen 4). Another system to note is a combined solar, geothermal, and compost heat recovery system developed in by a company in Omaha, NE. Water was first heated to 12.7 °C in a geothermal tank, heated a further 11 °C via solar energy, and then put into the in-pile compost system and warmed an additional 10 °C (Smith et al. S16). The pre-warming stage of this system keeps compost temperatures from being drawn down too low due to cool water temperatures entering the pile, causing a significant slowdown or even halt of the composting process.

In-pile hydronic heating compost systems have a wider variety of applications than the direct use compost systems, while being less complex than the system utilizing a condensing heat exchanger. Due to its simplicity and functionality, an in-pile system has benefits for a project like this. However, there are some drawbacks to this design that

should be considered. First, there is a limit to the energy recovery potential of these systems as compost does not generally have a high thermal conduction rate (Smith et al. S16). There is also concern with cold water bringing down the compost temperature too much. Piping inside the pile increases problems with maintenance and adjustments once the piping is installed, and the compost pile may not be able to be mixed. Design alterations and considerations would have to be made if working with this type of system.

C. Thermal Properties of Compost Materials and Hay

Some research has been done into determining the thermal properties of common composting materials. As the physical makeup of composting materials will often vary in terms of water content, bulk density, and particle size even amongst different samples of the same material, it is not possible to calculate an accurate single value for the materials' thermal properties. Work has then been done towards determining relationships between the factors influencing a compost material's thermal properties and the thermal properties themselves. Scientists at the Environmental Management and Byproduct Utilization Laboratory, National Soil Tilth Laboratory, Pennsylvania State University, and Iowa State University were able to develop linear relationships of thermal conductivity and volumetric heat capacity with water content and bulk density for a number of common compost materials (Ahn et al. 3980). This is critical information due to the importance of these thermal properties in accurate modeling of the compost process.

D. Anaerobic Digestion of Livestock Manure

Anaerobic digestion is becoming an increasingly popular alternative to traditional fossil fuels. In 2015, a study was completed by scientists at the National Technical University of Athens, Greece into the potential for energy generation through anaerobic digestion in Greece. Biogas is created through anaerobic digestion by bacteria breaking down biological, biodegradable waste and releasing biogas as a byproduct (Vlyssides 748). As agricultural wastes are extremely abundant and renewable, this is a valuable, easily obtained energy source. The best materials for biogas generation via anaerobic digestion have a water content of 50-55% and a carbon to nitrogen ratio below 30:1 (Vlyssides 751).

Livestock manure fits both of those qualifications, making biogas generation a viable option to both handle agriculture waste and produce energy.

In an anaerobic digester system, biogas is produced, captured, and converted into electricity or heat that can be used on-site or sold to a utility, or used directly as biogas for various purposes (Vlyssides 751). The amount of biogas produced in a system is influenced by many factors: the raw materials used, the temperature of the digester, the amount of material in the system, how long the energy source has been in the system, and what sort of digester is being used (Vlyssides 751).

Specifications

A. *Functional Requirements*

Before beginning the design work for the project, the functional requirements of the design were defined. The final design will be a system that creates heat from livestock manure in some form, while capturing that thermal energy generated. The system must then utilize the thermal energy produced to warm water and keep the water at that warmer temperature.

B. *Design Requirements and Criteria*

The following design requirements were discussed and established with advisor Annie Warmke and were based around her knowledge from farming and raising goats for many years. Careful consideration of design criteria important to farmers ensures the applicability of this design as a product and solution that will be useful to small farmers looking to cut energy usage and costs.

- Safety: The design should be safe for both the farmer/operator of the system and any livestock that may come into contact with the system.
- Cost: The design should be cost efficient; specifically, the combination of the material cost of the system and the cost to operate the system should be lower than the expenditures of farmers on heating water for livestock in winter.
- Durability: Any components of the design exposed to the weather or livestock should be durable and able to withstand repeated years of use.
- Sustainability: Materials for the system should be primarily composed of easily found/repurposed materials to ensure the design’s economic and environmental sustainability.
- Maintenance: The design should be easy to repair as needed and require little to no work to be kept in operating condition.
- Simplicity: The design should not be an overly complicated system or process. It should be simple in how it works and operates, to decrease costs and eliminate a high possibility of system failure.
- Ease of Use: The system should be easy to assemble and disassemble at the end of the season, if needed. It should be portable and easy to move.

Design Methodology

A. *Phase 1*

Phase 1 of the project focused on the determining the mixture of compost materials that would generate the maximum thermal energy and reach the highest temperatures. Four mixtures of compost materials were picked, each containing goat manure, hay, and an additional material that varied between mixtures. These materials included human manure, pine cones, and a combination of human manure and pine cones. The fourth mixture contained goat manure and hay alone, to act as the control variable against which the other mixtures would be measured. The human manure for this was partially composted waste obtained from an onsite composting toilet.

A wooden box was built with four sections, each section having measurements of 0.61 m wide, 0.61 m deep, and 0.46 m high, and installed in an outdoor area. This was done to create a small scale version of the heat generation that would be occurring in a full sized system. The box was in a shaded location but still exposed to normal day to day temperature fluctuations, to emulate outdoor conditions in which the designed system will be used and the materials will be composting. Each bin was filled with one of the following mixtures: a control box with only goat manure and hay with no additional material, a box with pine cones, goat manure, and hay, a box with human manure, goat manure, and hay, and a box with pine cones, human manure, goat manure, and hay. This setup can be seen in Table 1 below.

Table 1. Experimental Setup for Compost Material Testing

Goat Manure, Hay	Goat Manure, Hay, Pine Cones	Goat Manure, Hay, Human Manure	Goat Manure, Hay, Pine Cones, Human Manure

A Measurement Computing USB-500 temperature logger was placed in the middle of each bin about 0.20 m down from the surface of the mixture. Each logger was programmed to record the temperature inside the composting mixture every 15 minutes over the course of a month. This testing was completed from October through November

2017. After data collection was completed, the daily average temperature for each bin was calculated and graphed, along with the average daily outdoor air temperature for those dates (Figure 1).

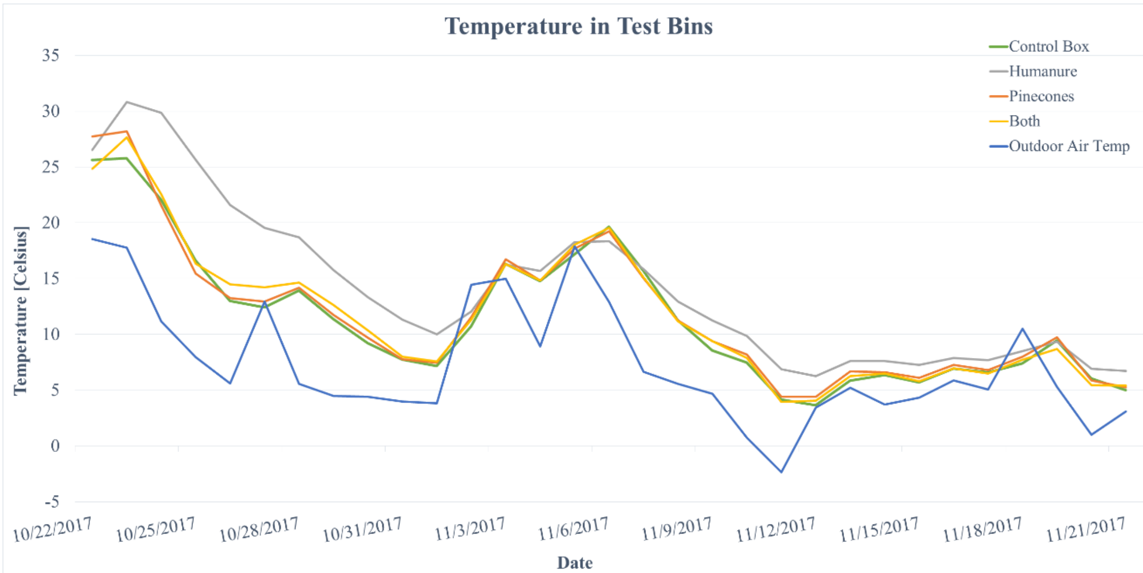

Figure 1. Graph Comparing Average Daily Temperatures of Test Bins

Table 2. Average Daily Temperatures of Test Bins

Date	Control Box (°C)	Human Manure (°C)	Pine Cones (°C)	Human Manure and Pine Cones (°C)	Outdoor Air Temp (°C)
10/22/2017	25.6	26.6	27.8	24.8	18.6
10/23/2017	25.8	30.8	28.2	27.7	17.8
10/24/2017	22.1	29.9	21.6	22.6	11.2
10/25/2017	16.6	25.6	15.5	16.3	7.9
10/26/2017	13.0	21.6	13.3	14.5	5.6
10/27/2017	12.4	19.6	12.9	14.2	12.9
10/28/2017	13.9	18.7	14.2	14.7	5.6
10/29/2017	11.4	15.8	11.8	12.6	4.5
10/30/2017	9.2	13.3	9.7	10.4	4.4
10/31/2017	7.8	11.3	7.8	8.0	4.0
11/1/2017	7.2	10.0	7.5	7.6	3.8
11/2/2017	10.7	12.1	11.5	11.3	14.4
11/3/2017	16.3	16.3	16.7	16.3	15.0
11/4/2017	14.8	15.7	14.8	14.9	8.9
11/5/2017	17.2	18.3	17.7	18.0	17.9
11/6/2017	19.7	18.4	19.2	19.6	12.9
11/7/2017	15.7	15.8	15.0	15.1	6.7
11/8/2017	11.3	12.9	11.3	11.2	5.6
11/9/2017	8.6	11.3	9.4	9.4	4.7
11/10/2017	7.5	9.9	8.2	7.9	0.7
11/11/2017	4.1	6.9	4.4	3.9	-2.3
11/12/2017	3.7	6.3	4.4	4.1	3.4
11/13/2017	5.9	7.6	6.7	6.3	5.2
11/14/2017	6.4	7.6	6.6	6.5	3.7
11/15/2017	5.7	7.3	6.1	5.8	4.3
11/16/2017	6.9	7.9	7.3	7.0	5.9
11/17/2017	6.6	7.7	6.8	6.5	5.1
11/18/2017	7.4	8.5	8.0	7.7	10.5
11/19/2017	9.4	9.3	9.7	8.7	5.3
11/20/2017	6.0	6.9	5.9	5.5	1.0
11/21/2017	5.0	6.7	5.3	5.4	3.1

When analyzing this data, it can be seen that the mixture containing goat manure, hay, and human manure stayed at higher temperatures and had the smallest fluctuations in temperature throughout the month when compared to the other mixes. All mixtures stayed at higher temperatures than the outdoor air temperature. However, there is a safety and health concern with the use of human manure in composting systems if the mixture does not reach high enough temperatures to kill pathogens. For health purposes, the mixture of

goat manure, hay, and pinecones was selected as the composting mixture as it behaved similarly to the other mixtures while still performing better than the ambient temperature.

B. Phase 2

While Phase 1 testing was being completed, three preliminary conceptual design ideas were generated: the radiant floor heating system, the biogas generator system, and the passive solar compost system. Each design idea was developed with the goal of maximizing the thermal energy being transferred to the water while fulfilling the design requirements and criteria.

i. Deep Bedding Heating System

The first conceptual design was developed out of the idea of radiant floor heating. In a radiant floor heating system, either electric resistance cables or piping of heated water is circulated under the floor of a room. As the floor warms, the warm air rises and heats the whole room uniformly. This creates an efficient, more passive heating system for homes and other buildings. Farmers utilize a similar concept when using the deep bedding method with their livestock. In deep bedding, livestock manure and hay is allowed to build up throughout the winter. As more hay and manure is added, the bottom buried layers begin composting, generating thermal energy and creating passive space heating.

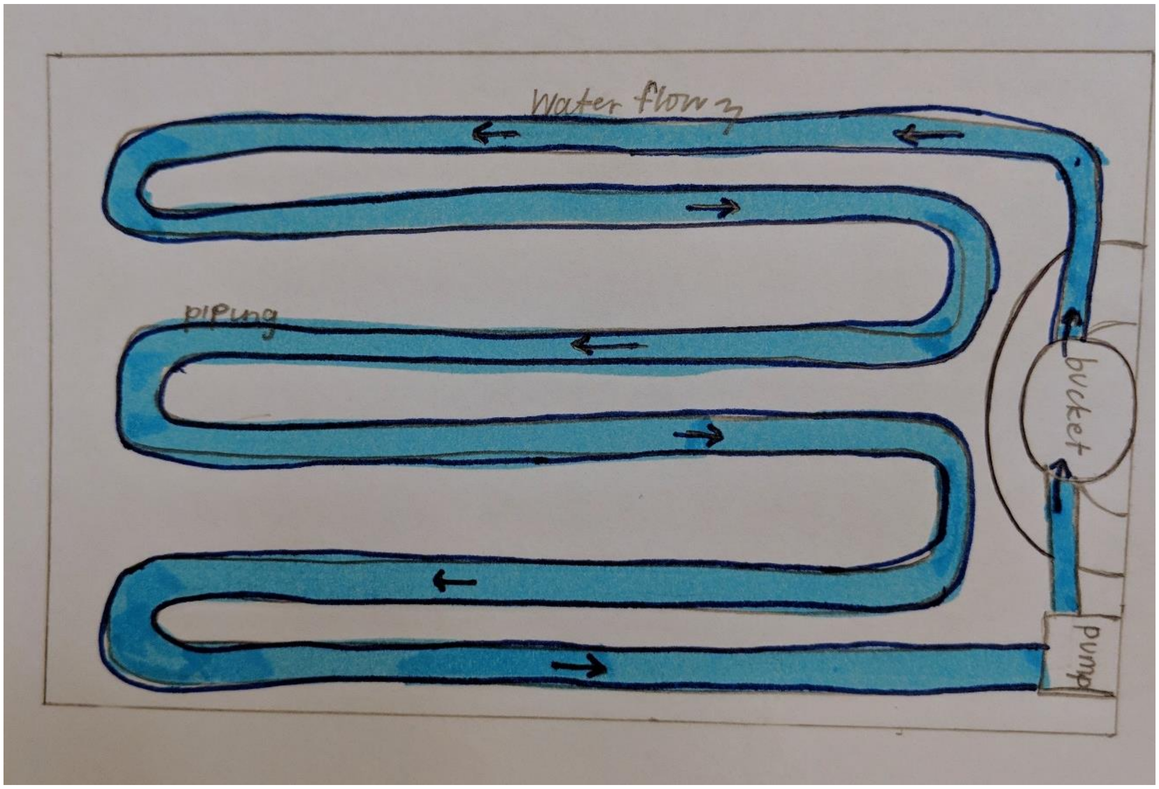

Figure 2. Conceptual Design 1

This deep bedding conceptual design combines deep bedding and radiant floor concepts with hydronic heating ideas from compost heat recovery systems. The design involves running cross-linked polyethylene tubing or copper piping parallel to the ground across the barn yard and barn stalls. Hay and manure for deep bedding would sit on top of and around the piping, creating heat as the hay and manure break down. Each end of the water piping would be attached to a bucket with a temperature sensor. When the water level gets too low or the water temperature gets too cold in the bucket, the sensor kicks on a small motor that pumps the cold water from the bucket and into the pipes in the deep bedding while refilling the bucket with hot water from the pipes in the deep bedding material.

ii. Biogas Generator System

The biogas generator design utilizes anaerobic decomposition of the hay and manure compost materials for the production of methane. As research into anaerobic digestion shows, biogas generation has a lot of potential being used for energy in a

number of applications. The methane created in this design would then be used as fuel in a water heater to bring water to an appropriate temperature for livestock.

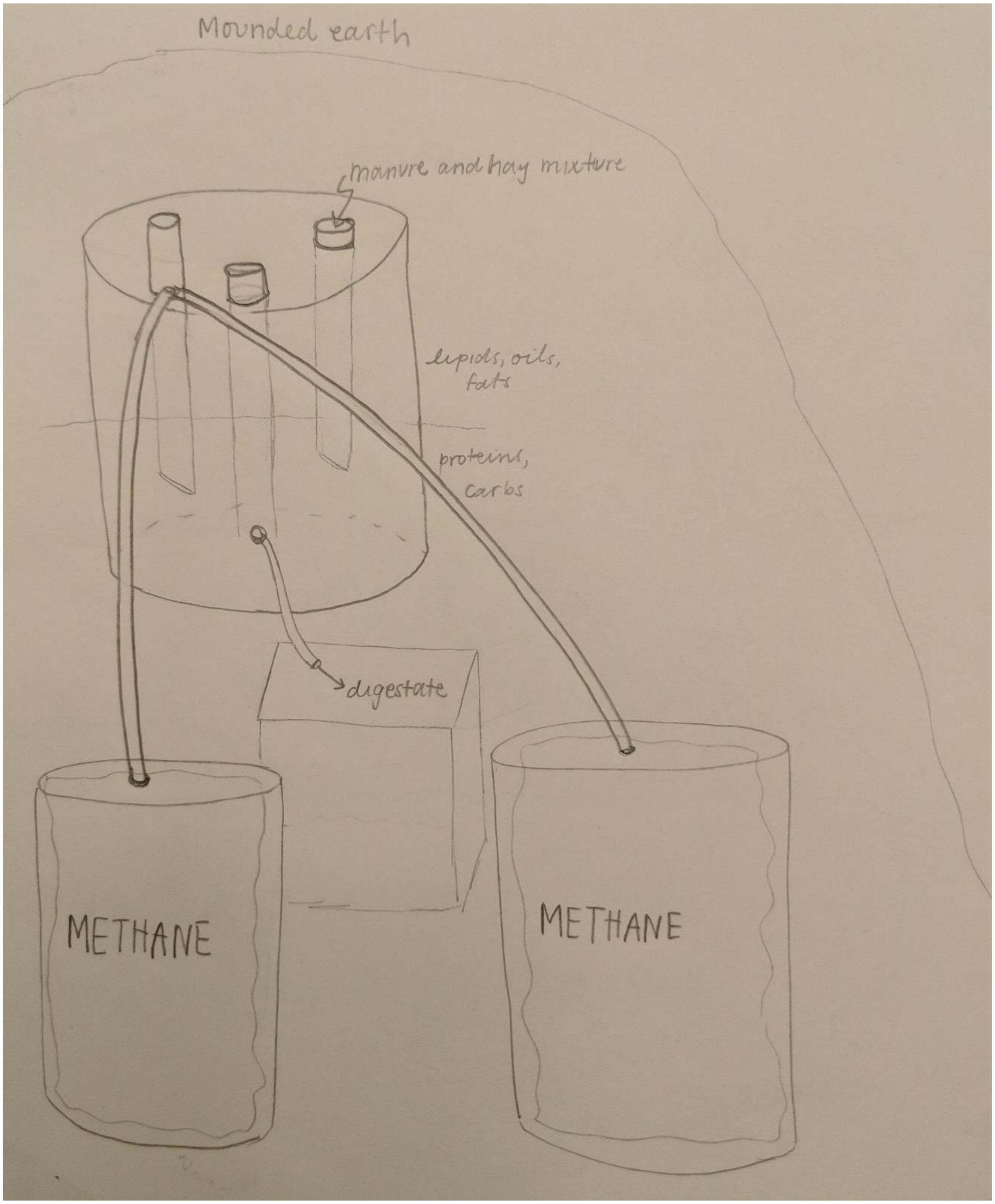

Figure 3. Conceptual Design 2

To create the biogas, a significantly different approach than the first design is needed. A 55 gallon rain barrel is drilled with three holes at the top with a long pipe in each and one hole drilled in the side near the bottom, creating a digester. The barrel is filled with the goat manure, hay, and any other composting materials, as well as water. The entire set up would be stored buried in a mound of earth. This would give insulation to the system, as the microbes and bacteria necessary for anaerobic digestion only create methane when in a range of temperatures higher than 10 °C.

In the anaerobic digestion process, methane and digestate are produced. One pipe acts as a gas outlet, allowing the methane to flow up the pipe and into one of two separate airtight rain barrels. The digestate, a wet mixture of leftover material after anaerobic digestion, would be siphoned off into a separate container through the hole in the side of the barrel and could be used as a soil amendment or crop fertilizer. As the materials in the digester break down, additional hay and manure will be added through the third pipe to keep producing methane. The methane is stored in airtight barrels until it is used to fuel a small hot water tank that warms water to the needed temperature.

iii. Passive Solar and Manure Decomposition System

The third conceptual design is a stand-alone system that uses passive solar energy and the heat from decomposing manure to generate thermal energy and warm water. In this design, a plywood bin is constructed and filled with a manure and hay mixture. The bin has an angled glass front portion, to allow for the capture of solar radiation during the day. A 55 gallon rain barrel filled with water is placed in the corner of the bin with water-filled piping running from the base of the barrel through the bin, parallel to the ground. As the manure and hay break down, energy is generated and transferred through the pipes into the water, bringing the water to a warmer temperature.

In this system, the water will be unmoving in the piping for the majority of the time. It will sit in the pipes and be warmed from all sides by the increasing temperature of the composting materials. When water is needed, a frost free spigot will be opened and the warmed water will flow through the pipes into the desired container. As the warmed water fills the bucket, it is replaced with cooler water from the rain barrel.

When the spigot is closed, water stops flowing and the cool, replacement water sits in the piping and is warmed until it is needed.

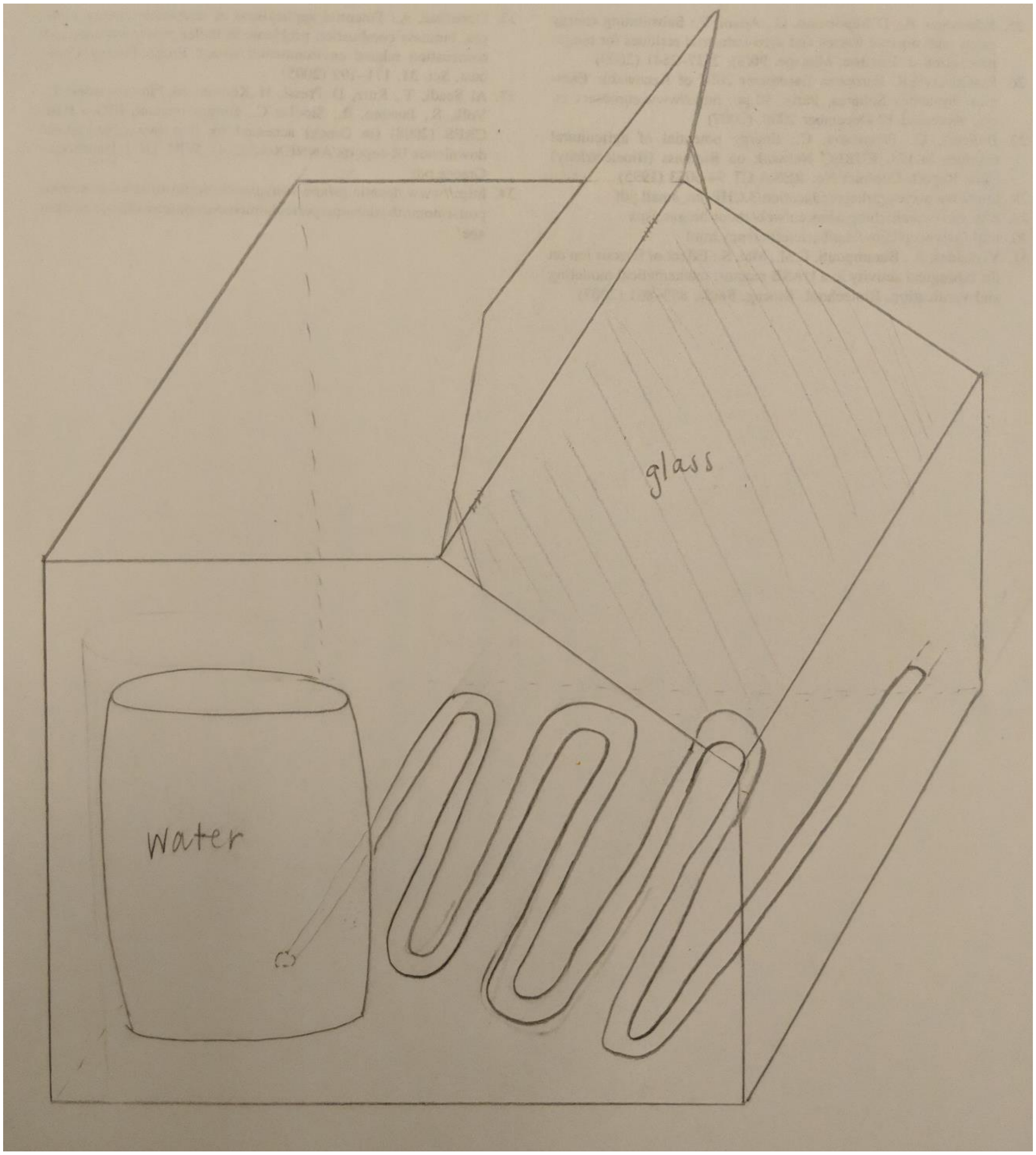

Figure 4. Conceptual Design 3

iv. Conceptual Design Decision Analysis

After developing the three conceptual designs, each concept was ranked on the design requirements and criteria to determine the best design to further develop. For each design requirement and criteria, each conceptual design was ranked on a scale of 1 to 5, with 1 being the worst and 5 being the best. The respective rankings were added for each design, and the design with the highest total score was selected as the best design with which to move forward in the design process. The conceptual design rankings are shown below (Table 3). Considerations for rankings are somewhat subjective, with the designs being ranked against each other just as much as being ranked against set values. For example, when ranking safety, the biogas generator was not necessarily unsafe, but was not as safe as the passive solar and deep bedding designs so is ranked the lowest. Concept 1 is slightly less safe than concept 3 as it involves direct interaction with the animals, so it is given a lower ranking than concept 3. Similar thought processes went into the design rankings for the other categories.

Table 3. Decision Analysis Chart

	Concept 1: Deep Bedding Heating	**Concept 2: Biogas Generator**	**Concept 3: Passive Solar and Manure Decomposition**
Criteria	Value	Value	Value
Safety	4	3	5
Cost	4	2	4
Durability	3	4	4
Sustainability	3	4	4
Maintenance	2	3	4
Simplicity	5	2	4
Ease of Use	4	3	3
TOTALS	**25**	**21**	**28**
Weight (1-5): 5 is the best, 1 is the worst, and the design with the highest score is the most preferable			

As seen in the table, the passive solar and manure decomposition system scored the highest. The deep bedding design has a lot of positive aspects, but it would be an intrusive system in its application. It must be laid on the barn floor before deep bedding

is added to the top, so it would have to be reassembled and disassembled every winter so as to not get in the way during the rest of the year. It is also virtually impossible to do any maintenance on the actual piping in the deep bedding, as feet of hay and manure deep bedding would build up on top of the pipes. However, it is a low-cost, simple option with a lot of potential, and could be redesigned into a less intrusive application.

The second design, the biogas generator, was ranked as the lowest scoring design. Though it is a more innovative application of manure decomposition, there are major safety concerns that make it a less than ideal design for this specific application. The production and capture of methane could be a safety hazard if not properly stored, and using a gas burning water heater near a barn full of hay does not optimize safety. With these safety concerns in mind, a redesign of this concept with appropriate infrastructure could yield a feasible biogas generator for a larger-scale application.

The passive solar and manure decomposition excelled overall. When compared to the other designs, it is the safest option, easiest to maintain, and relatively simple. As a stand-alone system, it will not be interfering with the barnyard and maintenance can more easily be done as needed. The simplicity of the design keeps material and labor costs low and allows for easy design adaptation in the future. It is also the safest system, as it is a passive system and is not accessible by livestock. Therefore, this design was selected to continue developing further.

Final Design Embodiment

Moving forward with the passive solar and decomposing manure design, the first step was further design development and improvement. First, rigid foam board insulation was added to the plywood bin design. Adding the foam board to the interior of the bin both insulates the bin contents to keep them at a higher temperature and adds a layer of protection between the decomposing materials and the plywood. Though rot resistant plywood can be used, the plywood will last even longer if not exposed directly to the decomposing manure and hay. Next, old car tires full of earth were added as a base for the bin. This design feature will keep the wood off the ground, decreasing the thermal energy losses through conduction and further extending the life of the plywood bin materials. Also added was a small PVC pipe at the top of the bin to the rain barrel to allow the rain barrel to be refilled with water as needed.

For the piping, copper pipes were selected to maximize the conductive heat transfer from the decomposing materials to the water. At a diameter of 0.75 inches, copper piping of length of 80 feet would hold around 2 gallons of water. In addition, a 96” long and 32” wide double paned glass window was selected as the material for the angled front of the bin. Double paned glass can more effectively capture solar radiation while decreasing thermal energy losses than a single pane of glass, further supporting a higher temperature inside the bin. In addition, a hinged insulated plywood cover the size of the glass window was added and can be closed at night to keep the bin warmer.

After the design was improved and any additions and changes were made, a Solidworks model was developed of the system with proper dimensions, materials, and material prices. Model drawings with dimensions can be found in the appendix. Figures 5 – 8 display the finalized design from different views. For this design, a lot of the materials were reclaimed and repurposed for this application. The tires, rain barrel, double paned glass window, and lumber were all materials that had been used previously and did not need to be purchased. This greatly increased the sustainability and conservation aspects of this design, while minimizing out of pocket costs and expenses. A materials list with specific products and prices can be found in the appendix.

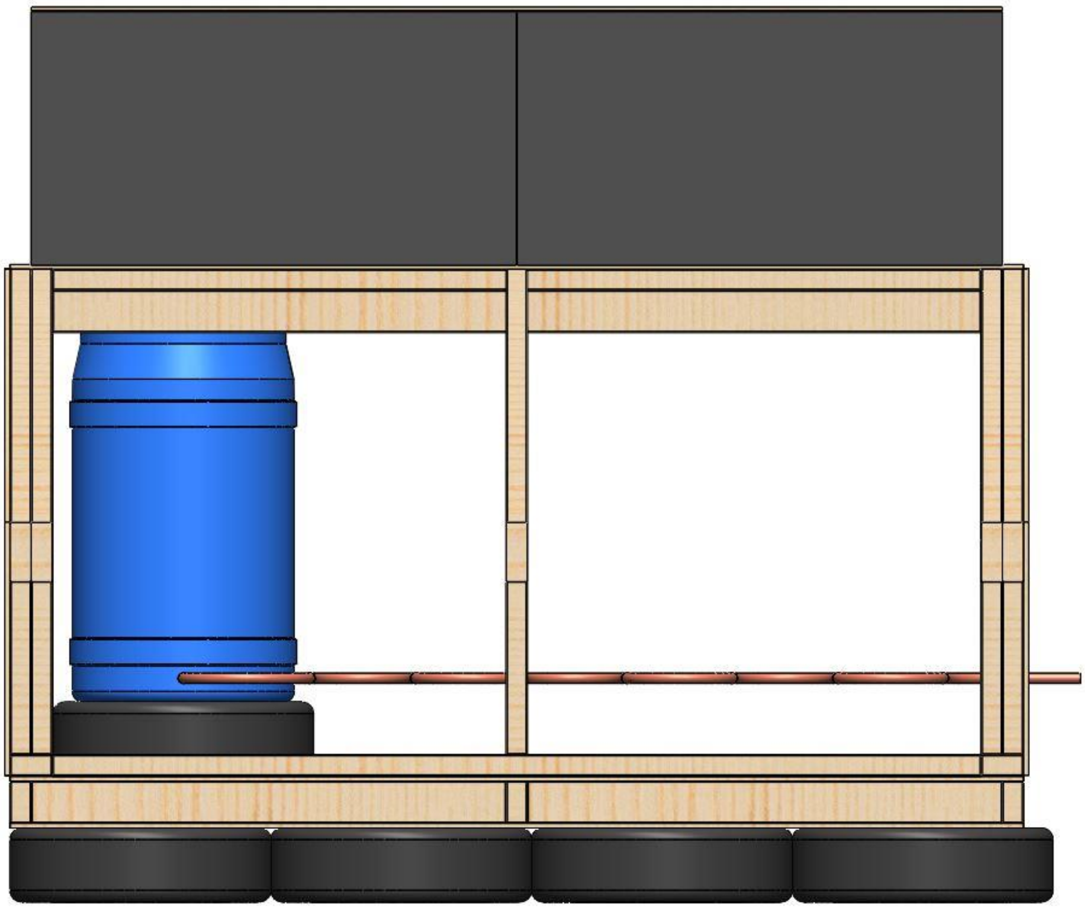

Figure 5. Front View of Final Design

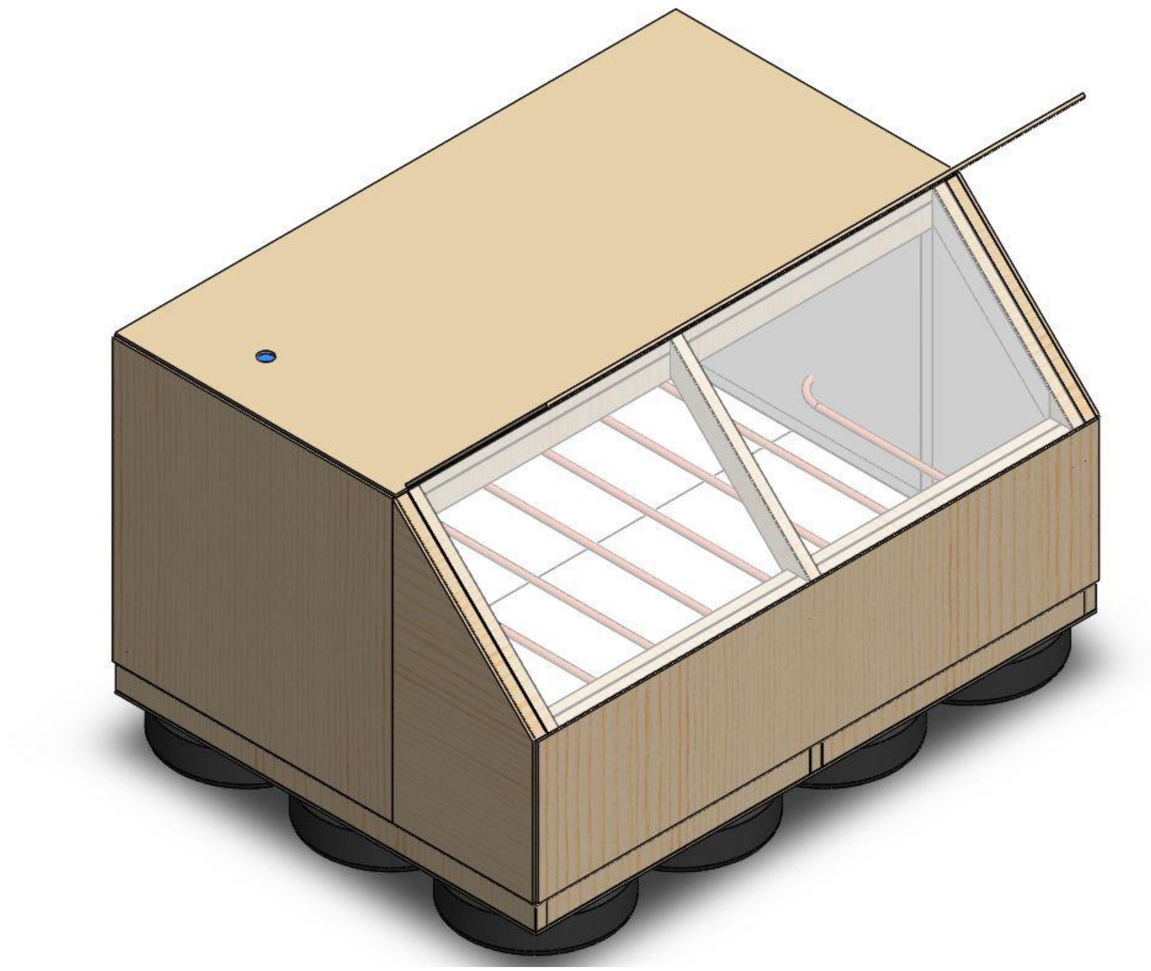

Figure 6. Isometric View of Final Design

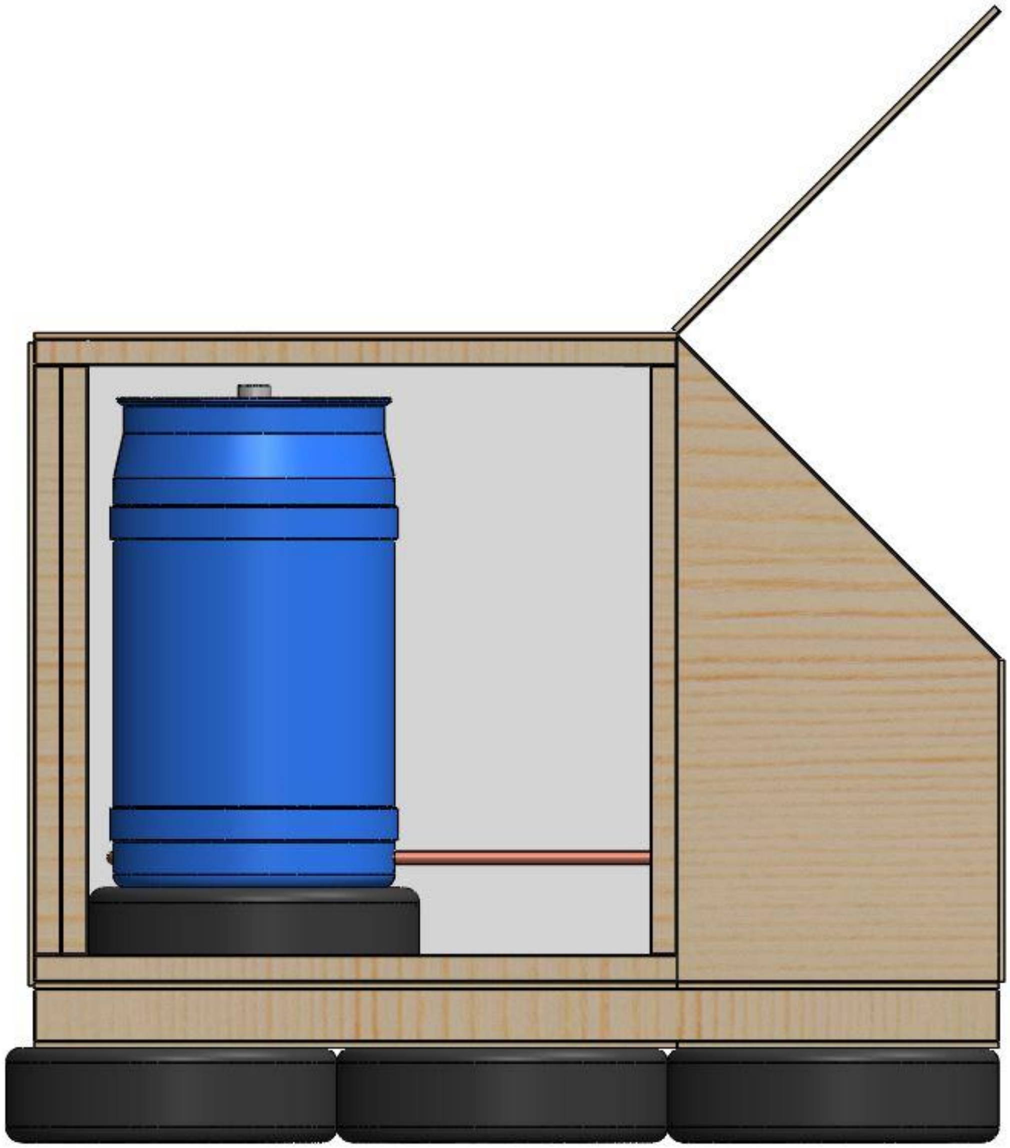

Figure 7. Side View of Final Design

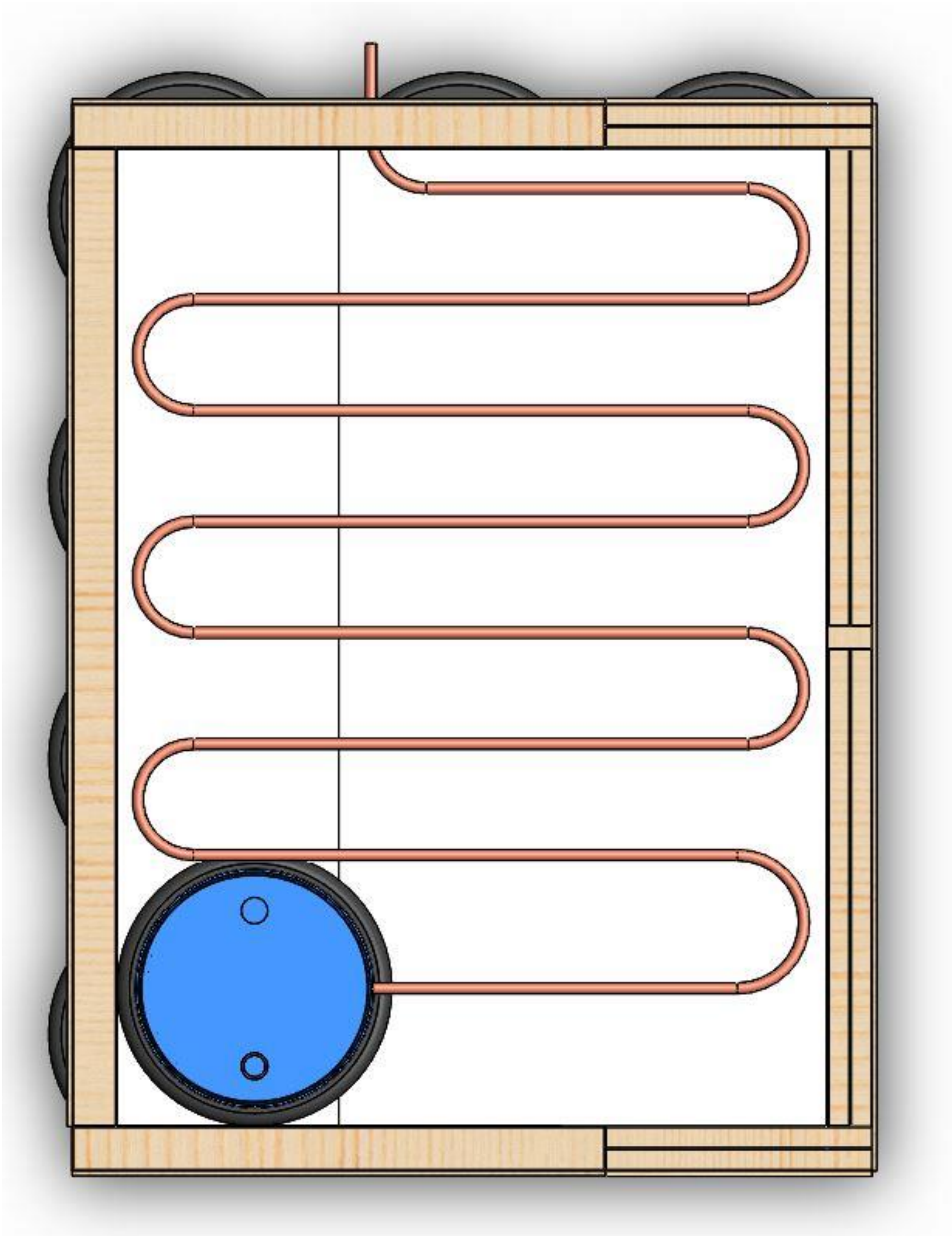

Figure 8. Top View of Final Design

Theory, Modeling, and Calculations

A. Theory

To test the system design, a MATLAB simulation code shown in the next section was created to model the water temperatures over an average day of use of the bin. The following assumptions were made to simplify calculations:

- The bin surface was assumed to have no heat transfer losses through the insulated plywood sides, with the only heat transfer happening between the glass surface and the outside world.
- The manure and hay decomposition process generates heat at a constant rate.
- Any entropy changes or heat loss due to water flowing through the pipes will be ignored.
- The interior of the bin is assumed to be a constant temperature with position, with no variation in temperature at any given moment in the bin.
- Conductive heat losses to the ground are minimized by the earthen tire foundation.

In the design, there are multiple modes of heat transfer occurring at the same time with thermal energy transfer happening between the system and the exterior environment and thermal energy transfer occurring within the system. Between the system and the exterior environment, there will be convection and solar radiation. Convection will be a transfer of energy out of the system into the surroundings and the solar radiation will be a transfer of energy into the bin. Inside the system, the primary mode of heat transfer is conduction through the composting materials to the pipe and into the water. There is also the energy generation occurring in the composting materials to be taken into consideration.

For calculating rate of energy transfer due to convection from the surface of the bin to the outside environment, the following equation was used:

$$Q_{convection} = h * A * (T_f - T)$$

where $Q_{convection}$ is the rate of heat transfer due to convection in W, h is the convective heat transfer coefficient in W/(m^2-K), A is the area of convection in m^2, T_f is the temperature of

the outside air in K, and T is the temperature of the surface of the bin exposed to the air in K.

For calculating rate of energy transfer due to solar radiation into the bin, the following equation was used:

$$Q_{solar\ gain} = SHGC * A * q_{solar}$$

where $Q_{solar\ gain}$ is the rate of heat transfer due to solar radiation in W, $SHGC$ is the solar heat gain coefficient of double-paned windows, A is the area of radiation in m^2, and q_{solar} is the solar irradiance on the surface in W/m^2.

For calculating rate of energy transfer due to conduction from the interior of the bin to the outdoor environment, the following equation was used:

$$Q_{conduction} = U_{eff} * A * (T_{bin} - T_{ground})$$

where $Q_{conduction}$ is the rate of heat transfer due to conduction in W, U_{eff} is the inverse of the effective R value of the soil, A is the area of conduction in m^2, T_{ground} is the temperature of the ground in K, and T_{bin} is the temperature of the bin in K.

When determining the energy generation of the decomposing manure and hay, there are no accepted values or constants for this as the energy generated in composting materials varies greatly with factors like ambient air temperature, moisture levels, free air space in the compost materials, and the materials to be composted. While testing of the full-scale system is being completed, additional tests can be done to determine the energy generation of the compost materials. Until additional testing is completed, an estimated energy generation value of 640 W/m^2 was used from a similar experimental setup (Smith et al. S14). This is a sizeable assumption to make, so testing to determine an accurate energy generation value is going to be extremely important.

The overall energy balance for the bin was calculated with the following equation:

$$Q_{solar\ gain} + (E_{generated} * V) - Q_{convection} - Q_{conduction} = E_{stored}$$

where $Q_{solar\ gain}$ is the heat transfer due to solar radiation in W, $E_{generated}$ is the energy generation of the decomposing manure and hay in W/m^2, V is the volume of the bin in m^2,

$Q_{convection}$ is the heat transfer due to convection in W, $Q_{conduction}$ is the heat transfer due to conduction in W, and E_{stored} is the change in energy inside the bin in W.

Assuming temperature does not depend on position inside the bin, the rate of change in energy stored inside the bin can additionally be expressed in the following equation:

$$E_{stored} = \rho c V \frac{dT}{dt}$$

where E_{stored} is the change in energy inside the bin in W, ρ is the density of the composting materials in kg/m^3, V is the volume of the composting materials inside the bin in m^3, and dT/dt is the change in temperature of the bin interior over time in K/s.

Once the change in bin interior temperature with time has been calculated, the rate of energy transfer from the bin into the water can be determined using the following equation:

$$Q_{conduction} = (T_{water} - T_{bin}) * R_{total}$$

where $Q_{conduction}$ is the heat transfer due to conduction in W, T_{water} is the temperature of the water in K, T_{bin} is the temperature of the bin in K, and R_{total} is the effective R value for the cylindrical pipe and water scenario. This R_{total} value is calculated using the following equation:

$$R_{total} = \frac{1}{h_{water} * \pi * ID * L} + \frac{\ln\left(\frac{r_{outer}}{r_{inner}}\right)}{2 * \pi * k_{copper} * L} + \frac{1}{h_{hay} * \pi * OD * L}$$

where h_{water} is the convective heat transfer coefficient of the water in W/m^2-K, ID is the inner diameter of the copper pipe in m, L is the length of the pipe in m, r_{outer} is the outer radius of the copper pipe in m, r_{inner} is the inner radius of the copper pipe in m, k_{copper} is the thermal conductivity of the pipe in W/m-K, h_{hay} is the convective heat transfer coefficient in the hay and manure material in W/m^2-K, and OD is the outer diameter of the copper pipe in m. It is important to note that this equation for conductive heat transfer differs from the conduction between the bin and the outside world. This is due to the cylindrical nature of the copper piping and water system—heat transfer is occurring radially along the length of

the pipe. This equation is based on the same conductive heat transfer premise as the conduction between the bin and outside environment equation, but this one calculates the change in temperature over the radial distance from the centerline of the water in the pipe to the exterior pipe surface.

B. MATLAB Modeling and Calculations

The following is the MATLAB code developed to model the passive solar and manure system. The ambient weather conditions for the model are from TMY2 weather data for Columbus, OH, and the conditions chosen are those that emulate the normal coldest day of the year. This allows the design to be tested in the weather conditions least conducive to an increase in water temperature. However, these parameters can be changed to model any day in the winter. Additionally, the model can be further developed to calculate the varying changes in bin and water temperatures each hour to get a more accurate look at the behavior of the bin and water.

```
clear
clc
close all
```

Summary

```
%The following code calculates the temperature of water in piping buried at
%the bottom of a bin filled with decomposing goat manure and hay.
%Calculations are made for a twelve hour period, using average solar
%irradiance, temperature, and wind speed data from TMY2 data for Columbus,
%OH. The coldest day of the year was selected, to design for the "worst-case" scenario.

%To simplify calculations, the change in temperature of the bin was
%calculated with respect to time (in seconds) and multipled by 3600
%seconds/ 1 hour to get an average temperature change in one hour. This
%change is assumed constant each hour and is then multiplied by 12 to get
%total temperature change over 12 hours (8 am - 8 pm).

%The starting temperature of the water each day is set to 13 degrees
%Celsius. This assumes the 55 gallons of water in the system are consumed
%every day, with the rain barrel being refilled in the morning each day.
```

Constants

```
V = (((96 / 12) * (24 / 12) * (48 / 12)) / 35.315) + ((((96 / 12) * (24 / 12)) * ((24 /
12) + (48 / 12))) / 2) / 35.315; %volume of bin [m^3]
cComp = 2159.6; %specific heat of compost: average of specific heat of alfalfa hay and
specific heat of manure [J/kg-degC]
rhoHay = 42.2; %density of alfalfa hay [kg/m^3]
rhoManure = 997.95; %density of goat manure [kg/m^3]
rhoComp = (rhoHay + rhoManure) / 2; %density of compost: average of density of alfalfa
hay and density of goat manure [kg/m^3]
```

Radiation

```
qsolar = 305.38; %average incident solar irradiance on glass front of bin over 12 hour
period (8am-8pm) [W/m^2]
SHGC = 0.766; %solar heat gain coefficient of double paned window
Ar = ((96 / 12) * (32 / 12)) / 10.764; %area of glass front of bin [m^2]
qrad = SHGC * Ar * qsolar; %heat transfer due to radiation [W]
```

Energy generated

```
egen = 640; %energy generated by compost decomposition per unit volume [W/m^3]
Egen = 640 * V; %energy generated in bin [W]
```

Convection

```
Aconv = ((96 / 12) * (32 / 12)) / 10.764; %area of convection --> glass front of bin
[m^2]
Nu = 1; %Nusselt number set at 1
rho = 1.225; %density of air [kg/m^3]
vel = 2.154; %average wind speed over 12 hour period (8am-8pm) [m/s]
Lc = 8 / 3.281; %characteristic length
mu = 177.1E-7; %dynamic viscosity of air [N-s/m^2]
cpAir = 1006.7; %specific heat of air [J/kg-K]
kAir = 25.1E-3; %thermal conductivity of air [W/m-K]

To = -6.45 + 273.15; %average ambient temperature outside of bin over 12 hour period
(8am-8pm) [K]
Ts = 0 + 273.15; %beginning temperature of bin (assumed to be 0deg C) [K]
T2 = To;
T1 = Ts;




Re = (rho * vel * Lc) / mu; %Reynolds number to calculate h value
Pr = (mu * cpAir) / kAir; %Prandtl number to calculate h value

if Re < 5E5
    Nu = (0.664*(Re^0.5))*(Pr^(1/3));
else
    Nu = (0.037*(Re^0.8))*(Pr^(1/3));
end

hconv = (Nu * kAir) / Lc; %convective heat transfer coefficient [W/m^2-K]
qconv = -(hconv * Aconv * (T2 - T1)); %heat transfer due to convection [W]
```

Conduction

```
Acond = ((96 / 12) * (48 / 12)) / 10.764; %area of glass front of bin [m^2]
Rsoil = 0.42; %Effective R value of soil
Ueff = (1 / (Rsoil));
```

```
Tground = To; %Starting temperature of ground assumed equal to ambient air temperature
[K]
Tbin = Ts; %beginning temperature of bin [K]

qcond = -(Acond * Ueff * (Tground - Tbin)); %heat transfer due to conduction
```

Energy balance

```
estored = qrad + Egen - qconv - qcond; %energy balance of system to calculate energy
stored in bin [W]
dTdt = estored / (rhoComp * cComp * V); %change in temperature with respect to time due
to stored energy [K/s]

dT = dTdt * 3600; %change in temperature in one hour [K]
```

Change in temperature of water

```
ID = 0.019939; %inner nominal diameter of 0.75" L type copper pipe [m]
OD = 0.021082; %outer nominal diameter of 0.75" L type copper pipe [m]
L = 24.384; %length of pipe in bin [m]
kcop = 401; %thermal conductivity of copper pipe [W/m-K]
Tw = 13 + 273.15; %beginning temperature of water [K]
cpWater = 998.9; %specific heat of water [J/kg-K]
Vwater = pi * (ID/2)^2 * L; %volume of water in pipes [m^3]
rhoWater = 997; %density of water [kg/m^3]
hwater = 1; %convective heat coefficient of water in pipes [W/m^2-K]
hhay = 2; %convective heat coefficient in hay in bin [W/m^2-K]
mwater = Vwater * rhoWater; %mass of water [kg]

RWater = 1 / (hwater * pi() * ID * L); %equivalent R value in water
Rcyl = (log((OD/2)/(ID/2)))/(2*pi()*kcop*L); %equivalent R value through copper pipe
Rhay = 1 / (hhay * pi() * OD * L); %equivalent R value in hay
Rtot = RWater + Rcyl + Rhay; %total equivalent R value

Qr = -((Tw - (Tbin + (dT * 12))) / Rtot); %heat transfer from bin through to water, with
12 hours of temperature change
Qrh = Qr * 3600; %thermal energy transferred into water over 12 hours [J]

TwFinal = (Qrh / (mwater * cpWater)) + Tw; %final temperature of water over 12 hour
period [K]
Twfinal = TwFinal - 273.15; %final temperature in Celsius
Tchange = TwFinal - Tw;
```

Final Results

```
Radiative Heat Transfer = qrad;
Convective Heat Transfer = qconv;
Conductive Heat Transfer = qcond;
Heat Transfer through Pipe Into Water = Qr;
Final Water Temperature = Twfinal;
Change in Water Temperature = Tchange;
```

```
table(RadiativeHeatTransfer, ConvectiveHeatTransfer, ConductiveHeatTransfer,
HeatTransferthroughPipeIntoWater, FinalWaterTemperature, ChangeinWaterTemperature)

%In the results table below, radiative heat transfer, convective heat
%transfer, conductive heat transfer, and heat transfer through the pipe
%into the water are in W. Final water temperature and change in water
%temperature are in degrees C.
```

Results/Analysis

The passive solar and manure decomposition water heating design does successfully achieve the project goal of increasing the temperature of the water in the system, while maximizing safety and sustainability and lowering costs. In phase 1, it was determined that a mixture of goat manure, hay, and pine cones would be the most suitable mixture of composting materials. Phase 2 led to the development of the passive solar design system, using the previously mentioned mixture as the composting materials in the system.

A full-scale system to test the design and calculations was not able to be completed due to time constraints and the weather-dependent nature of the research. The design assumptions and models were then not able to be validated against test data; however, the model results shown in Table 4 display a positive increase of 7.9 °C in water temperature throughout the day when using conservative estimates and assumptions for temperatures and energy generation.

Table 4. Results from MATLAB Modeling

Variable Name	Values	Units
Radiative Heat Transfer	463.6	W
Convective Heat Transfer	47.0	W
Conductive Heat Transfer	45.7	W
Heat Transfer into Water	16.7	W
Final Water Temperature	20.9	°C
Change in Water Temperature	7.9	°C

These results are promising and show a lot of potential for the design as further model development, testing, and system validation are completed.

Improvement and Future Steps

There are a number of future steps to take to continue to improve the design and build of this system. The first of these considers the complexity of the MATLAB model used to calculate water temperatures in the system. A few assumptions were made to simplify calculations and allow for an estimate of water temperatures on an average day. Moving forward, the model could be further developed to look at varying weather conditions and temperatures, to consider additional transfers of thermal energy, and to account for a varying temperature with respect to location in the goat manure and hay composting material. This would give a more accurate idea of what water temperatures might be achievable in the system.

As changes to the MATLAB model are being completed, the next step would be to finish building the full-scale physical system. Once this is built, test data would be gathered to validate the system model and further improve water temperature predictions. This would also inform any design changes or modifications that might need to be made to the original design.

Upon successful testing and validation of a functioning full-scale physical system, the feasibility of automating the system can be determined. The current design is completely passive, with only the potential energy of the stored water driving the water flow through the system. When hot water is needed, a person must go to the bin, turn the spigot and fill a bucket, and take that water to the livestock. If the system could be mechanized to decrease the amount of direct labor needed from the farmer or other personnel, this would save a lot of time and money. Automating this would involve giving livestock direct access to the water in an insulated trough and installing a controller and sensor system to detect water level and water temperature in the trough. When the water reaches too low of a temperature or too low of a level, the controller would signal a pump to kick on and pump additional hot water into the trough.

Turning the system into an automated system with constant access to the water requires the design of an insulated, protected water trough for the livestock. When working with goats specifically, if any sort of contaminant or residue gets in the water they will not drink it. The water will also cool faster and possibly freeze if sitting in an open trough exposed to the ambient air. A prototype insulated trough must then be designed and

constructed to keep the animals from contaminating the water and to keep the water warmer longer. Basic testing has been completed in teaching goats to eat from a covered food dish, with a lid that must be pushed down to access the food. A lidded trough could be a good first prototype to use, as the goats have shown they can easily learn to use a system like this.

In addition, energy generation values for decomposing goat manure and hay are not known to a great level of accuracy. With further testing and research, more accurate values can be determined. This could offer more insight into the correct ratios to maximize energy generation, possible better materials to be used in other designs, and a bank of data for future research and testing.

Summary and Conclusions

The final design of the passive solar and manure decomposition system demonstrated that the concept for this design achieves the design requirements and criteria and sets up steps for testing of a full-scale system. Though the project goal of a built and tested full-scale system was not met, the rest of the project goals were. An appropriate and effective compost material mixture was chosen, multiple conceptual designs were developed and reviewed, and a final water heating design with measurements and materials was completed and is ready to build and test. In addition, MATLAB simulating and modeling was started to predict the expected behavior of the system and the temperature of water that could be reached.

From the design process and model results, it can be concluded that the passive solar energy and manure decomposition water heating design is an effective system to create a significant change in water temperature. Though there are still design improvements that can be made, the basic system meets the project goal. The MATLAB model demonstrates this, but can also be further improved with an increase in model complexity. With future steps working towards quantifying some of the assumptions made in design and modeling, an even better prediction of water temperature will be able to be made.

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Appendix

A. Materials List

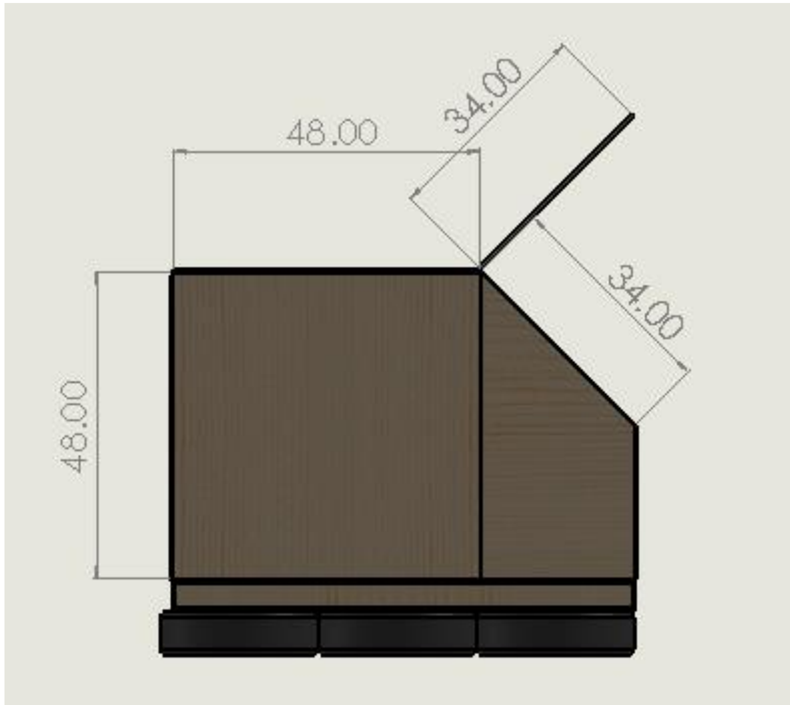
Below is the list of materials needed to build the full-scale system for model validation and testing, along with materials costs. This shows every component at purchase cost (not considering some supplies as already being acquired, etc).

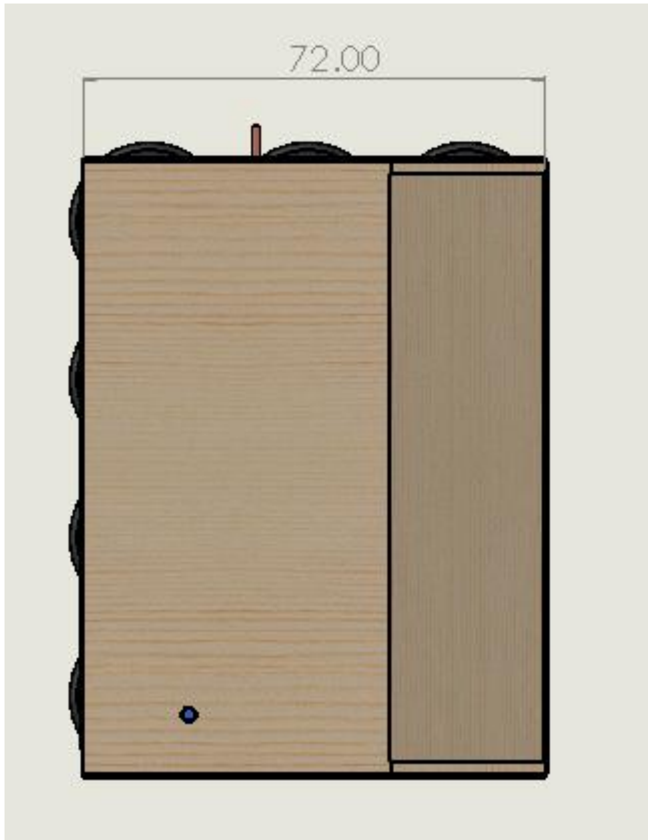
Description	Mfr.	Mfr. P/N	Qty.	Unit Cost	Total Cost	Notes
Pressure treated Plywood 1/2in 4ft X 8ft	Home Depot	166081	8	$ 30.98	$ 247.84	
Pressure treated 2x4 by 10ft	Home Depot	253920	17	$ 6.77	$ 115.09	
Great stuff insulation 16oz	Home Depot	99053937	1	$ 4.25	$ 4.25	$3.83 for 12 or more
Plastic Panel 1/16in 4ft by 8ft	Home Depot	63003	5	$ 19.98	$ 99.90	
Rigid Foam Insulation 2in 4ft by 8ft	Home Depot	310891	4	$ 24.65	$ 98.60	
Plastic Rain Barrel, Blue, 55gal	Home Depot	PTH0935	1	$ 99.99	$ 99.99	with diverter kit
LEXAN 48 in. x 96 in. x .177 in. Clear Polycarbonate Sheet	Home Depot	11600101	1	$ 130.19	$ 130.19	Other thicknesses more expensive for this size
Tires 215/45R17			12		$ -	Free?
36 in. x 48 in. x .118 in. Acrylic Mirror	Home Depot	AM3648S	2	$ 90.16	$ 180.32	Significantly cheaper than a 96in sheet
1/2 in. x 14 in. Brass Anti-Siphon Frost Free Sillcock Valve with Push-Fit Connections	Home Depot	P140-8-12x14	1	$ 35.49	$ 35.49	
Dull 304 Stainless Steel Surface-Mount Hinges with Holes Removable Pin, 6" x 1-1/2" Door Leaf	McMaster-Carr	1586A21	4	$ 12.47	$ 49.88	
3/4 in. x 10 ft. Copper Type L Hard Temper Straight Pipe + fittings + add'l plumbing hardware	Home Depot	3/4 L 10	8	$ 21.56	$ 172.48	
Total Estimated Cost					**$ 1,234.03**	

Some supplies were repurposed or recycled from previous applications, with the new materials list and costs for the system shown below:

Description	Mfr.	Mfr. P/N	Qty.	Unit Cost	Total Cost	Notes
Supplies Already Secured:						
Plastic Rain Barrel					$ (99.99)	
Tires					$ -	
Acrylic Mirror					$ (180.32)	
Remaining Supplies Needed:						
Pressure treated Plywood 1/2in 4ft X 8ft	Home Depot	166081	8	$ 30.98	$ 247.84	
Pressure treated 2x4 by 10ft	Home Depot	253920	17	$ 6.77	$ 115.09	
Great stuff insulation 16oz	Home Depot	99053937	1	$ 4.25	$ 4.25	
Plastic Panel 1/16in 4ft by 8ft	Home Depot	63003	5	$ 19.98	$ 99.90	
Rigid Foam Insulation 2in 4ft by 8ft	Home Depot	310891	4	$ 24.65	$ 98.60	
3/4 in. x 10 ft. Copper Type L Hard Temper Straight Pipe + fittings + add'l plumbing hardware	Home Depot	3/4 L 10	8	$ 21.56	$ 150.92	
1/2 in. x 14 in. Brass Anti-Siphon Frost Free Sillcock Valve with Push-Fit Connections	Home Depot	P140-8-12x14	1	$ 35.49	$ 35.49	
Dull 304 Stainless Steel Surface-Mount Hinges with Holes Removable Pin, 6" x 1-1/2" Door Leaf	McMaster-Carr	1586A21	4	$ 12.47	$ 172.48	
Remaining Estimated Cost					**$ 924.57**	

B. Dimensioned Solidworks Drawings

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