COLD CLIMATE HOUSING RESEARCH CENTER
CCHRC

Thermal Storage Technology Assessment

An introductory assessment of thermal storage in residential cold climate construction

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Contents

Acronyms 5

Introduction 6

1. Thermal Storage Fundamentals..... 7
   1.1 Definition 7
   1.2 Uses of thermal storage 7
   1.3 Basic types of storage..... 10
      1.3.1 Sensible heat storage 10
      1.3.2 Latent heat storage (phase change materials) 11
   1.4 Active vs. passive thermal storage..... 15

2. Design Considerations..... 16
   2.1 Method of charging thermal storage 16
   2.2 Storage material..... 17
   2.3 Time frame 18
   2.4 Temperature range 18
   2.5 Size 19
   2.6 Efficiency 20
   2.7 Retrofit and new construction considerations 21
   2.8 Commercialization of thermal storage..... 21

3. Thermal Storage Examples..... 23
   3.1 Electrical thermal storage (ETS) 23
   3.2 Biomass technologies..... 23
   3.3 Solar thermal systems 24

Synthesis of Findings..... 27

Research Recommendations..... 29

Works Cited..... 30

Appendix A: Literature Resources 32

Appendix B: Thermal Storage Systems in Cold Climates 38
   Wood boiler thermal storage for daily cycling 38
   Seasonal storage of solar and wood energy in Fairbanks 40
   Seasonal storage of solar and wood energy in Homer 42
   Off-peak power use of a ground source heat pump..... 43
   Electric grid stabilization through the use of thermal storage..... 44
   Solar thermal storage with water tank and soil 45
   District solar thermal heating system..... 46
   Seasonal storage of solar energy in Edmonton..... 48
   Wood boiler thermal storage for multi-day heating 49

Appendix C: Sample Thermal Storage Calculations..... 50

Acronyms

AFUE	Annual Fuel Utilization Efficiency
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.
BTU	British Thermal Unit
C	Celsius
CCHRC	Cold Climate Housing Research Center
COP	Coefficient of Performance
DOE	Department of Energy
EPS	Expanded Polystyrene
ETS	Electrical Thermal Storage
F	Fahrenheit
PCM	Phase Change Material
PHPP	Passive House Planning Package

Introduction

Space heating accounts for 74% of energy consumption in single-family residences in Alaska (ARIS, 2012), while domestic hot water heating accounts for 15 – 25% of home energy use in America (U.S. Department of Energy, 2011). As such, researchers and residents of Alaska and other heating-dominated climates are continually searching for methods to raise efficiencies and reduce costs. One such method that has recently attracted attention in Alaska is thermal storage, which is currently being used in Alaska and other cold climates in conjunction with heating systems. For instance, a thermal net-zero home was recently built in Fairbanks. The heating system uses solar thermal panels and a masonry heater to charge a 5,000-gallon thermal storage tank that provides heat to a radiant floor for space heating. The thermal storage tank also provides heat for the domestic hot water system. The potential of thermal storage to enhance the use of renewable heating systems in cold climates, increase the efficiency of heating systems, and reduce emissions has raised interest in its use.

In spite of its potential, there are few informational resources on the successful application of thermal storage in cold climates. Currently, there are limited educational materials and literary articles on thermal storage systems in cold climates, and on how thermal storage can be best integrated into a heating system. This report aims to provide an informative, though introductory, assessment of the current status of thermal storage in residential construction in cold climates. The authors' primary motivation is to provide building researchers and building owners living in cold climates with a document outlining the applications and potential of thermal storage in heating systems. It is hoped that this document can also be used to inform and define future research on thermal storage in cold climates.

This report consists of three main sections, which are a compilation of preliminary findings from literature research and interviews with homeowners in cold climates on the topic of thermal storage for use with residential space heating and domestic hot water systems. First, readers will find *Thermal Storage Fundamentals*, with general definitions and information on the different types and uses of thermal storage. The second section, *Design Considerations*, includes information on characteristics of thermal storage, its efficiency, and construction considerations. Lastly, *Thermal Storage Examples* contains more details about three commonly used methods of charging thermal storage systems. The report concludes with a *Synthesis of Findings* on thermal storage, and *Research Recommendations* on the types of research that could help advance the use of thermal storage. Readers interested in further pursuing the topic will find short summaries of relevant literature in *Appendix A: Literature Resources*. Also, for case studies of thermal storage installations located in cold climates, please see *Appendix B: Thermal Storage Systems in Cold Climates*. Finally, for those interested in the calculations necessary for designing a thermal storage system, there are a few sample calculations in *Appendix C*.

1. Thermal Storage Fundamentals

Thermal storage is more common than one might think: many households use water storage tanks to provide domestic hot water on command for uses such as washing dishes, washing hands, and showers. These storage water heaters range in size from a few gallons to more than 100 gallons, contain heating elements or burners to heat cold water and maintain its temperature before providing hot water on command to the faucet. Less frequently, thermal storage can be used in space heating systems to store heat for a length of time. Some examples include the storage of solar energy from solar panels for overnight heating and the seasonal storage of heat for use in winter in a district heating system. In either case, thermal storage can be thought of as a "heat battery" because it stores heat energy to be released later.

1.1 Definition

Thermal storage is a technology that stores thermal energy for later use. All thermal storage systems have three functions:

1) Charge: A heat source is used to provide heat to the storage medium.
2) Storage: The storage medium is used to store the heat for later use. The storage medium may be located at the heat source, at the discharge location, or at another location.
3) Discharge: The heat leaves the storage medium in a controlled fashion to be used for another purpose.

Additionally, all thermal storage systems will consist of three basic parts:

1) The storage material, and, if applicable, a container for the storage material.
2) A heat exchanger to facilitate heat transfer to and from the storage material.
3) A control system that facilitates the charging and discharging of the thermal storage.

Despite the similarities in function and basic parts, there are many variations in the way thermal storage systems are configured. Many are designed specifically for a particular residence or application, and are truly one-of-a-kind. Others follow a general approach with small modifications for a particular installation.

1.2 Uses of thermal storage

Thermal storage is a mechanism used to accomplish a goal, such as heating with renewable energy instead of fossil fuels, increasing the efficiency of a heating appliance, or providing energy security. Once the objective of the system is specified, the design and building of the thermal storage system can begin.

One of the purposes of thermal storage is to smooth out a mismatch between supply and demand of energy. In many cases, this makes the use of a renewable resource for space heating functionally practical. For instance, a buffer tank of water can be charged with a solar thermal system during the afternoon when heating is not typically needed, and store the heat for use at night and early morning. A larger storage system might be designed to store solar heat for cloudy days. In both cases, the use of thermal storage allows a heat source with intermittent delivery to be used to deliver heat at other hours. Thermal storage can be used with other intermittent energy sources, such as wind or industrial waste heat. Industrial waste heat can be stored to later help warm up the equipment for re-start, or it can be re-routed to be used for space heating. Other intermittent sources of heat can come from biomass appliances such as outdoor wood boilers. Thermal storage allows owners to fire the boiler efficiently and for longer periods of time, instead of having to start a burn every single time the building calls for heat.

The charging of thermal storage from an intermittent source is illustrated in Figure 1 and Figure 2. In Figure 1, where there is no thermal storage, the heat source sometimes provides heat at a time when the heat load is high. However, other times, the heat source produces heat when it is not needed, or the heat load is calling for heat when there is no heat source. Figure 2 shows a system that utilizes thermal storage. In this scenario, the heat load draws from the thermal storage, so it does not matter if the heat load is high when the heat source is unavailable.

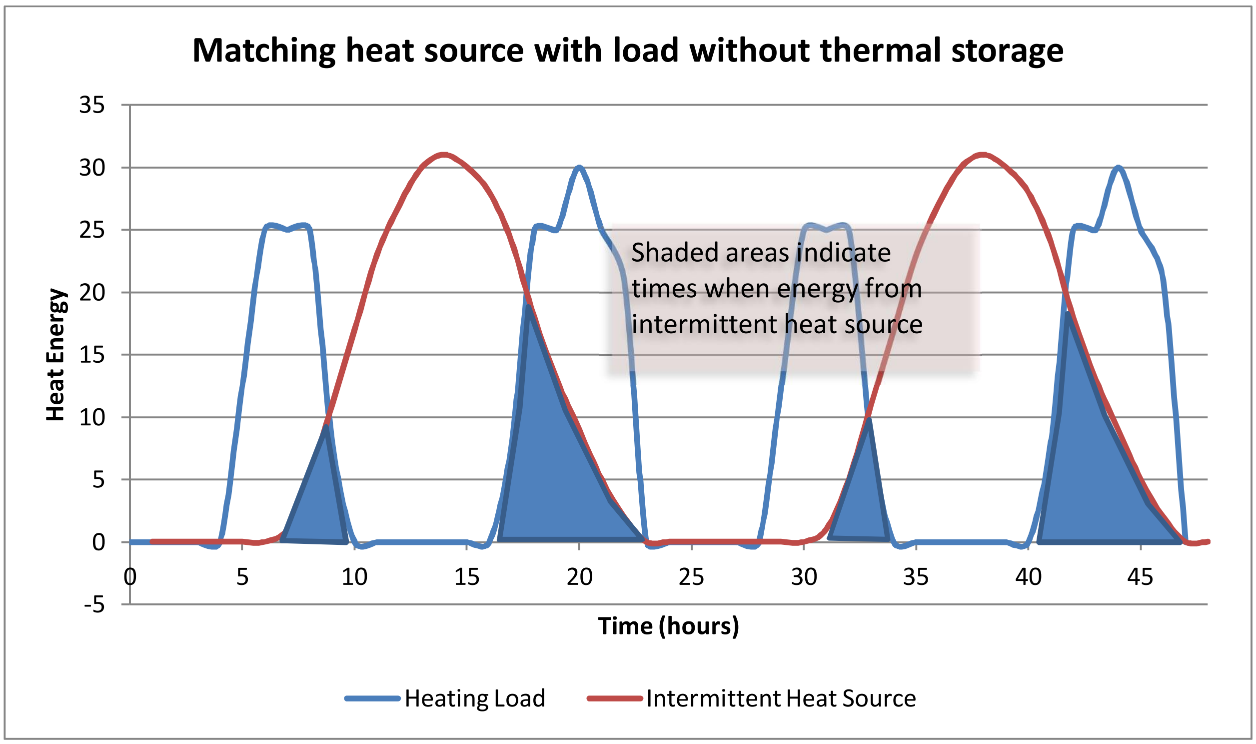

Figure 1: This graph shows an example of a heat source that only occasionally matches with a heat load.

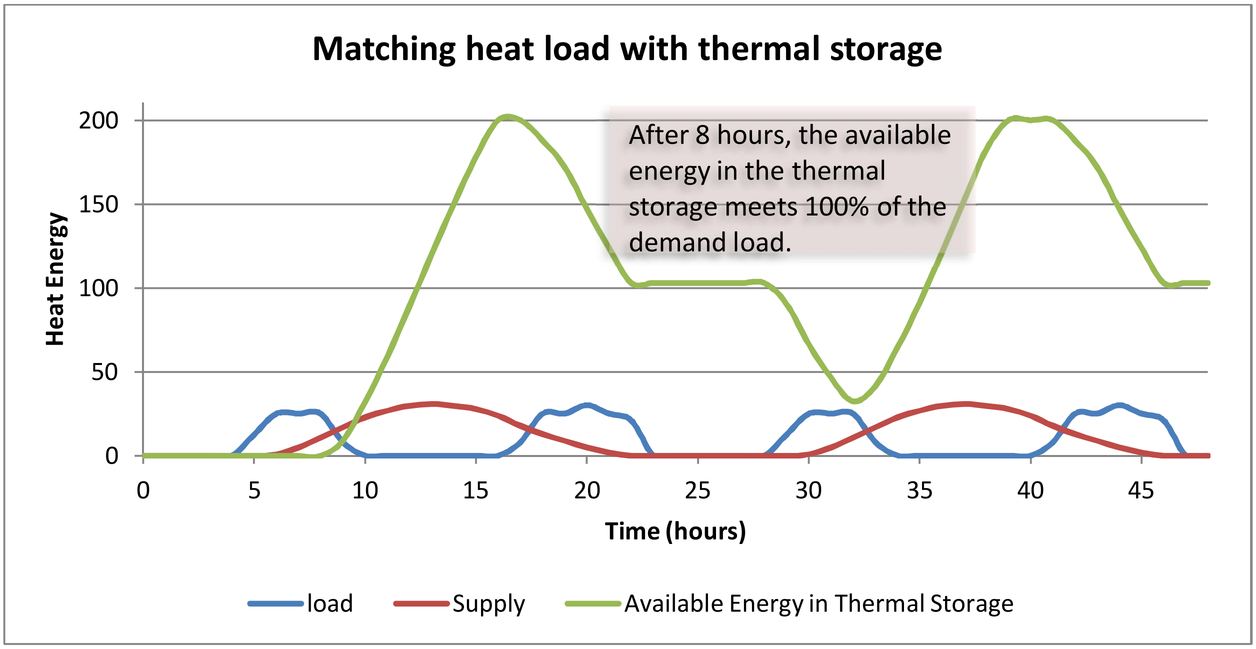

Figure 2: This figure shows how thermal storage can accept heat from heat sources and distribute it at a different time to a heat load.

For electrical heating systems, thermal storage can be used to enable the purchase of off-peak power, which costs less than power during peak usage times for utilities that provide off-peak power pricing. This type of system is used on a daily or twice-daily charging schedule. During off-peak power times (typically early afternoon and after 10 p.m.) an electric heater or ground source heat pump is used to heat a buffer tank of water or another storage system. The thermal storage then provides heat to a hydronic distribution system during the remainder of the day. Thermal storage can also be used as a thermal dump for excess electricity, such as when a renewable electrical source, like solar photovoltaic panels, produces more electricity than the grid needs. Excess electricity can be converted into heat, stored, and used for space heating. In combined heat and power systems, thermal storage allows for more continuous operation. Many cogeneration systems operate to meet thermal demand, resulting in excess electricity at times when it is not needed. It also causes systems to cycle on and off to meet partial load heat demands. Thermal storage allows systems to operate for longer periods of time to charge the thermal storage instead of cycling on and off (Haeseldonckx, Peeters, Helsen, & D'haeseleer, 2007).

Many other thermal storage applications exist, including providing energy security for buildings such as hospitals that experience large consequences if there are interruptions in service. Thermal storage can also be used in space cooling applications, for instance, by using the storage of winter ice to provide space cooling during the summer (Dincer & Dost, 1996). Basically, thermal storage can be used for any number of applications in all types of buildings.

1.3 Basic types of storage

Thermodynamics dictates that there are three types of thermal storage: chemical, latent, and sensible heat storage. Chemical energy storage refers to when heat is stored in reversible chemical reactions. Currently, this type of system is not commonly used for residential applications and is not discussed in this report.

The other two types of storage, sensible and latent, refer to heat that can be stored in a material. As heat energy is added to a solid, two processes happen. First, the temperature of the solid goes up. The heat added that causes the temperature change is called “sensible heat.” Secondly, when the temperature of the solid reaches the melting point, the solid undergoes a phase change to a liquid. During the phase change, heat is added to the material, but the temperature remains constant. The heat needed for the phase change is referred to as “latent heat.” The same process is repeated if heat continues to be added to the material. First, the liquid’s temperature rises (due to the sensible heat) and then it undergoes a phase change to become a gas (due to the addition of latent heat). In the reverse order, heat is released from the material as it cools. Latent heat is released during phase changes from a gas to a liquid, and from a liquid to a solid, and sensible heat is released as the temperature of the substance drops between phase changes. These two types of heat storage are discussed in more depth below.

1.3.1 Sensible heat storage

In this type of storage, energy is stored by a change in the temperature of a storage material. Technically, the storage material can be any material, but water, oil, rock, soil, and ceramic are common choices. The storage material is kept in an insulated container to prevent heat loss (exceptions include ground and aquifer storage). A heat exchanger is used to bring heat to storage medium while it is charging, and to take heat to a distribution system when the stored heat is needed.

The storage material can be a solid, liquid, or gas. However, solids and liquids, which generally have a higher heat capacity than gases, are most commonly used for storage in residential space heating applications. Solids are simple to store in an insulated container. It takes more effort to store a liquid, as the container must be leak-proof, but liquids have the advantage that they can also be used for heat transfer – for instance, the liquid might run in pipes to solar thermal panels. Gases are not commonly used as their volume changes significantly with temperature change, and a container must be leak-proof.

The amount of heat that can be stored in a material depends on the amount of material present, and its specific heat. The specific heat capacity (c_p) is the amount of heat needed to raise one kilogram of a substance by 1°C. Higher specific heats means that more heat can be stored in a material in a given temperature range.

$$Q = mc_p\Delta T$$

The amount of sensible heat (Q) stored in a mass is given by the equation above. A larger mass (m), a higher specific heat (c_p), and a larger temperature change (ΔT) all yield a greater heat storage capacity in the mass. The amount of sensible heat that can be stored is limited by the phase change temperature. Once the phase change temperature is reached, additional heat will cause a phase change. As storage containers are typically not designed to accommodate a phase change, the phase change temperature represents a maximum temperature for the thermal storage system. For instance, water is a common storage medium for sensible heat systems.

However, water boils at 212°F (at sea level pressure) so if systems need storage of a higher temperature range than this, a different storage medium should be used. In higher temperature systems, rock is often used as the storage medium.

The thermal conductivity of the material does not limit its heat storage capability, but it is important to consider because it affects the rate at which heat can be added or extracted from the storage material, especially for solids, which do not experience significant heat transfer by convection. A higher thermal conductivity indicates that heat transfer will occur more quickly.

Sensible heat systems are often thermally stratified. This means the storage material will have thermally distinct horizontal layers so that it is colder at the bottom of the storage container and warmer at the top. Ideally, the stratification will be great enough that there is a 10-20°F difference between the hot and cold temperatures. A common design for enabling stratification in liquid sensible storage is a tall, cylindrical tank of water with controlled fluid flow into and out of the container to minimize mixing. Stratifying devices can increase the thermal efficiency of the heating system by delivering warmer fluid to the heating distribution system while sending lower temperature fluid to the heat source (Pinel, Cruickshank, Beausoleil-Morrison, & Wills, 2011).

1.3.2 Latent heat storage (phase change materials)

In latent heat storage, heat is stored at nearly constant temperature in a phase change of the storage material. The storage materials for latent heat storage are known as Phase Change Materials (PCM). They are manufactured for many different temperatures, allowing them to be matched to specific applications. Currently, there are only a small number of PCM demonstration systems in existence, as they are still in a research and development phase (Bruno, 2004).

There can be liquid-solid, liquid-gas, and solid-solid phase transitions. Solid-solid transitions occur in substances that have different crystalline structures, and that require the addition or release of heat to change between the different structures. Liquid-solid transitions are currently the most common: there are relatively few solid-solid PCMs, and liquid-gas PCMs are not as practical for residential uses as those with a solid-liquid transition because they generally require load temperatures higher than are useful in residential heating systems. Also, containers for gases must be leak-proof, and allow for any expansion of gas as it increases in temperature.

For any phase change, the latent heat is absorbed or released at constant temperature. The latent heat (Q) stored or released in the phase change is given by:

$$Q = mL$$

A larger mass (m) or larger specific latent heat (L) results in a larger amount of latent heat storage. The specific latent heat of each substance is the amount of heat needed to change one kilogram of the substance from one phase to another. Each substance has a latent heat for each phase change (solid-liquid, liquid-gas and, if applicable, solid-solid) and the latent heat is unique to that substance. Of course, latent heat systems will also have sensible heat storage below and above the phase change temperature.

An example of the storage capacity of a PCM is shown in Figure 3. Note that the storage capacity of the medium can change based on the lowest useful temperature required by the heating device. In Figure 3, the lowest useful temperature required for heating, or the temperature required by the distribution system, is shown at 70°F. The phase change occurs at 100°F. The amount of heat storage capacity is linear with temperature with a significant step increase in energy at the phase change temperature.

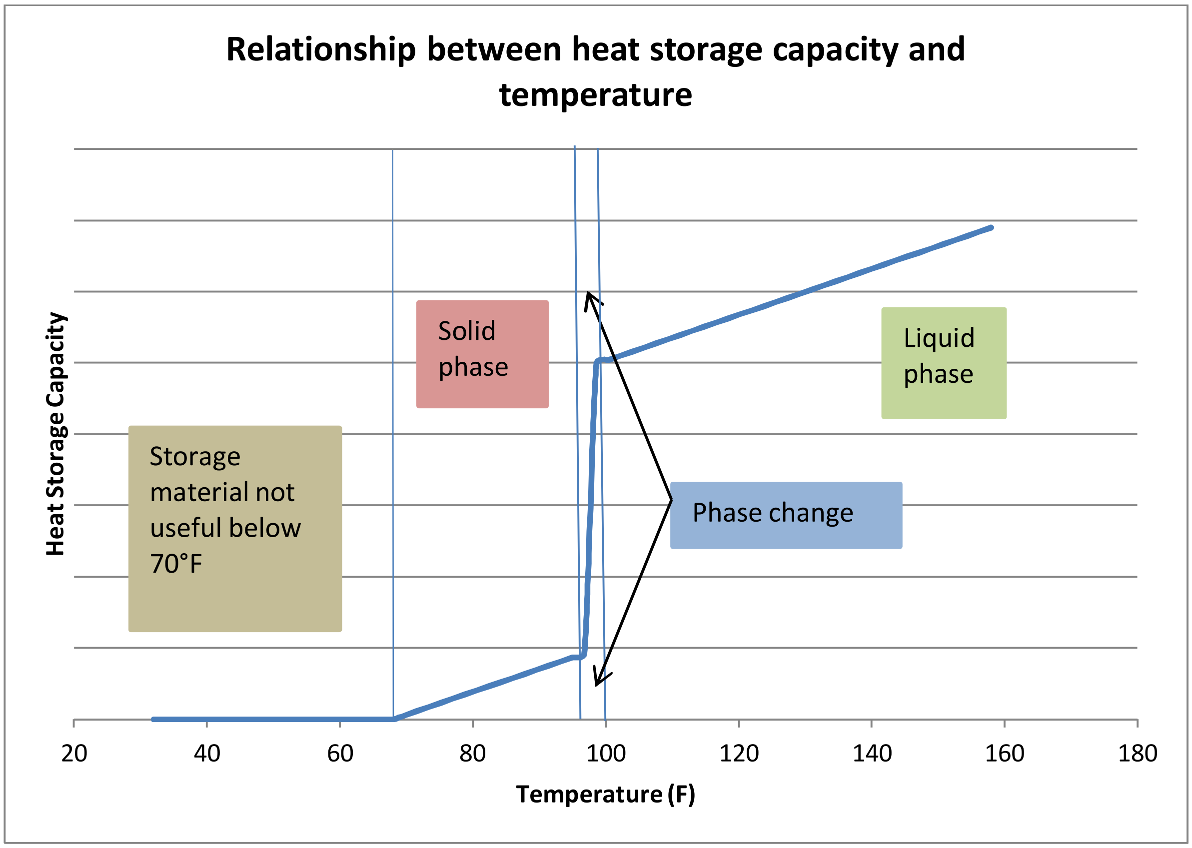

Figure 3: Heat capacity of an example material from 20-180°F. The lowest useful temperature required for heating in this case is shown at 70°F.

For heating applications, the useful heating load temperature must be below the phase change temperature, or the benefit of the step increase in the storage system due to latent energy is not experienced. Additionally, the heat source must be able to raise the temperature of the storage medium above the phase change temperature in order to utilize the latent heat capacity of the PCM. It is important to choose a PCM with phase change temperatures that are above the heating load temperature, and below the heat source temperature.

When used in thermal storage systems, PCMs are stored in a container. The container can be large, or the thermal storage can consist of several small containers, such as tubes or plastic bags, of PCMs. Shallow and thin containers are ideal, as they lessen stratification while in the liquid phase and helps ensure there is a uniform temperature throughout the container. This prevents the chemicals in certain types of PCMs from separating, which would hinder solidification (Demirbas, 2006). Containers with large surface areas also help with heat transfer with PCMs that do not have a high thermal conductivity, by exposing more surface to the heating mechanism. The heat stored in PCMs in active systems is transferred to and from the PCMs with mechanical or electrical aid.

Ice is one example of a PCM that can absorb heat at its phase change temperature of 0°C (32°F). To visualize how ice absorbs heat, think of when it is placed in a glass of soda: When the temperature of the soda is above the melting point of ice, the heat from the soda is absorbed by ice as it changes from solid to liquid, keeping the soda at the desired temperature.

There are several materials that can be used as PCMs. PCMs can be classified as organic, inorganic or eutectic (Tyagi & Buddhi, 2007). Organic materials include paraffin and non-paraffins and inorganic materials include metals and salts. A eutectic is a certain composition of two or more substances, which has a lower melting point than a composition with different amounts of the substances. Eutectics almost always melt and freeze without separating because they freeze into a crystalline structure and then melt simultaneously. The challenge with finding a material to use as a PCM is to find one with as many optimal characteristics as possible. The following table contains a list of optimal characteristics.

Table 1: PCM Characteristics

Desirable Characteristic	Explanation
High chemical stability	Chemically stable PCMs can handle a larger temperature swing and more varied storage conditions.
High energy storage density	A high latent heat per unit volume allows more heat to be stored with less material. This takes up less space in the building.
High thermal conductivity	A high thermal conductivity will allow for faster heat transfer.
The melting temperature should match the use of the thermal storage system.	PCMs have different melting temperatures. This allows them to be customized to the particular heat load and heat source.
Small change in volume during the phase change	Substances that change in volume during phase change must have storage containers that can accommodate the volume change. A smaller volume change requires less space and allows the storage container to be smaller.
Not flammable	PCMs that are non-flammable are desirable since they do not pose a potential hazard to property or occupants.
Low cost	Lower cost must be weighed with other characteristics, but a lower capital cost will make the system more attractive to homeowners.
High availability	Available substances are easy to obtain during the initial purchase and can be replaced when necessary.
Long life span	Appropriate PCMs should show little to no degradation after high numbers of melting cycles.
Recyclability	As PCMs do not last forever, it is important to consider if they can be recycled when their lifetime has ended. Builders should consider what the lifetime is and how to dispose of the material when the useful life is over.
Low corrosivity	Non-corrosive PCMs are easier to store because they do not require special storage containers or heat exchangers.
No need for supercooling	Some materials must be “supercooled,” or cooled below their freezing point in order for crystallization to occur. Ideally, PCMs will begin to store latent heat when their freezing point is reached, without the need for supercooling.

PCMs are the subject of many current research studies. For example, topics in current research focus on enhancing the thermal conductivity of PCM materials, on how to incorporate them into construction materials, and on using numerical simulation to evaluate their performance in buildings (Zhou, Zhao, & Tian, 2011). Also, there is still research being done on what materials are optimal and on what methods are efficient for transferring heat to and from PCMs, especially those used in passive heating systems. Another branch of PCM research focuses on finding or creating compounds with promising characteristics (Zhou, Zhao, & Tian, 2011).

1.4 Active vs. passive thermal storage

Thermal storage as defined above is referred to as "active thermal storage" although, in practice, and in this paper, the "active" is often not included in the name. Active thermal storage systems are distinct from passive thermal storage systems in that they are designed to be charged and discharged at specific times and/or at the command of a control system. Additionally, active systems use mechanical systems (such as a pump or fan) to facilitate their charge and discharge. For instance, a solar thermal system uses a control system, a heat exchanging fluid, a pump, and pipes to move heat from solar thermal panels to a storage tank. Passive systems generally accept and discharge heat without the use of controls. An example of a passive system is a passive solar heating system. A passive solar system allows a large mass that is often part of the building materials to be charged by sunlight coming in through windows; sunlight might charge a concrete floor during the day, and then the concrete floor will radiate this heat into the room during the evening and night. Of course, some houses have a mix of passive and active systems to provide their heating. In the following sections of this report, unless otherwise specified, thermal storage will refer to active thermal storage.

Passive thermal storage is often incorporated into buildings to smooth out temperature swings, delay heat entry (such as with a Trombe wall, a thick masonry wall that absorbs solar heat and conducts it into a room over the course of several hours), absorb energy surpluses such as solar heat or heat from computers or other appliances, or to store heat as part of a passive solar heating system. Bricks, concrete, masonry, earth, and logs are some materials that can be used in buildings as passive thermal storage. Passive thermal storage absorbs heat when the temperature is above that of the thermal mass and later releases it as the ambient temperature cools off to below the thermal mass temperature. The heat does not come from a specific source as with active thermal storage, and there is typically not an exchange mechanism. As such, passive systems do not have thermal mass contained in a single insulated storage container, but rather integrated into the building structure or envelope. It does not need a distribution system, because it releases heat directly into a room when the ambient temperature cools below the temperature of the thermal mass.

An example of a system that bridges the passive and active definitions is a masonry heater. Masonry heaters have a specific source of heat – the fire in the firebox – that is charged on a schedule chosen by the building resident. Because of this, the masonry heater is not a completely passive system. However, the heater does contain thermal mass in the form of several hundred pounds of masonry or rock, which captures the heat from the burn and slowly releases it to the surrounding space. Masonry heaters release the heat stored in their thermal mass over a period of several hours – the surface temperatures of some masonry heaters take more than 24 hours to return to ambient temperature (Lilly & Misiuk, 2007). A masonry heater is an efficient way to "bank" heat for the night if a fire is burned during the evening. Masonry heaters can be combined with active thermal storage to provide space heating for areas of a home that require a distribution system. For these systems, a heat exchanger coil is located in the masonry heater firebox. The fire is used to heat fluid in a heat exchanger, which is subsequently transferred to the thermal storage medium that then releases heat through an actively controlled heat distribution system. This type of system can be used with solar thermal panels to provide heat when the amount of sunlight is low.

2. Design Considerations

There are a great variety of thermal storage systems. They can be distinguished first and foremost by two main characteristics: the method of charging the thermal storage and the material used for storage. Other characteristics of systems include the length of time heat is stored for, the amount of heat stored, the design of the heat exchangers, and the heat distribution system.

Choosing how to combine these characteristics should be based on a well-developed objective that should specify how much heat needs to be stored for what length of time. The method of charging the storage and the storage material can then be chosen based on availability, cost, and compatibility with the building needs. Finally, builders must consider how the design and type of thermal storage they have chosen will affect the cost, reliability, and performance of the space heating system (Dincer & Dost, 1996).

2.1 Method of charging thermal storage

Any heat source can be used to charge a thermal storage material. However, thermal storage complements certain heat sources more than others. For instance, many renewable heat sources are intermittent sources and do not match up supply with demand without the use of thermal storage. Some methods of charging thermal storage include solar thermal systems, wind electric heating systems, biomass systems (such as wood boiler), and industrial waste heat.

The choice of a heat source is often motivated not only by the availability of the fuel, but also the desires of the building owner. For instance, many businesses and homeowners wish to use renewable resources such as solar and biomass. Others simply want or must live “off the grid” or have identified a waste heat source that can be used to reduce heating costs.

The heat source must be of sufficiently high temperature to charge the thermal storage system to a high enough temperature that it can be used by the distribution system. Different distribution systems require different temperatures of fluid to distribute heat to a space. Some common distribution systems and their temperatures are listed in the table below.

Table 2: Common distribution systems

Distribution System	Temperature
Forced air	Air, 120 – 150 °F
Hydronic baseboard	Water, 150 – 180 °F
Hydronic radiator	Water, 120 – 180 °F
Hydronic radiant floor	Water, 85 – 100 °F
Domestic hot water systems	Water, 120 – 140 °F

2.2 Storage material

The choice for a storage material, like the one for a heating source, is similarly dependent on both practicality and owner preference. The current variety of storage materials, and the lack of standard thermal storage systems, allows for flexibility in choosing a storage material and tailoring the design of the system to the specific application.

The choice for a storage medium should be based on a number of factors (Pinel, Cruickshank, Beausoleil-Morrison, & Wills, 2011), such as the specific heat capacity or phase change temperature of the material, the temperature range over which the material will be heated, and the cost of the material. The chemical properties of the material, such as its corrosiveness, toxicity, and ability to stratify with temperature will also affect how optimal it is for a specific installation.

Additional considerations for the storage material include how to store it, how to transfer and collect heat from the material, and how to control thermal losses from the storage container. Considerations must also be made to account for the potentially significant volumetric changes of the storage medium based on changes in temperature.

For sensible heat storage, water, rocks, and soil are common choices. Water, in particular, has a number of advantages. It is inexpensive, easily available, safe, can be blended with glycol for freeze protection, and its low viscosity allows it to be pumped easily. Also, the specific heat of water is 4-5 times greater than that of sand. Solid materials such as rock have their own advantages, such as no need for a leak-proof storage container. High-density ceramic bricks are often used for electric thermal storage. Soil is often already in place, if the storage material uses ground outside the house (for example, a heating system which stores summer solar heat in the ground to be extracted in the winter). For smaller homes, the option to use thermal storage outside of the house frame is an advantage. The variety of storage materials allows the homeowner to choose the one that works for their circumstances.

Latent heat storage is still in an experimental phase, but a promising feature of PCM is the great variety of phase change temperatures of the materials in existence. The phase change temperature of the material can essentially be tailored to the temperature of the demand-side heat. For instance, there are different grades of paraffin that have freezing points in the range of 100 to 160°F (Sharma, Tyagi, Chen, & Buddhi, 2009). As these materials move from a research and development to mass-production, they should offer a storage alternative that can be customized to an installation.

2.3 Time frame

Thermal storage systems can be designed to store heat for a wide range of time frames, from a few hours to several months. In each case, storage systems are charged with heat, which is then stored for a length of time before discharging occurs.

Table 3: Heat storage time frames

Time frame	Example
Less than one day	Electrical Thermal Storage (ETS) Devices: off-peak utility power systems, which might charge thermal mass each afternoon and night. Handles hourly loads.
One day (diurnal storage)	Solar or biomass thermal space heating systems in mild climates. Handles daily loads.
A few days	Solar thermal space heating systems and domestic hot water in mild climates that typically experience cloudy days. Handles daily loads for several days despite intermittent cloudy days.
Several months (seasonal storage)	Space heating systems that use seasonally available solar resource to charge storage during the summer to be used in the winter

The length of usable time and amount of usable heat stored in the medium will depend on the user's needs, the heat source, and the design of the system. However, there are advantages and disadvantages to short timeframe and long timeframe systems that are important to consider when deciding on a heating system. Systems that are recharged daily will have a smaller size, and thus a lower capital cost, than a seasonal system. Smaller systems are typically manufactured off-site. On the other hand, seasonal storage, while more expensive and voluminous, reduces the reliance on any one day of thermal charging, which increases the reliability of the system. For instance, a few cloudy days do not make much difference over the course of a year for solar thermal seasonal storage (Dincer & Dost, 1996). Also, seasonal storage can be used for district heating systems, heating systems that provide heat to multiple homes, where capital and maintenance costs can be shared.

2.4 Temperature range

Thermal storage systems can store heat at virtually any temperature. In fact, they can also be used in space cooling applications – some systems store ice to be used for cooling during the summer. The storage temperature, or temperature range in the case of sensible storage, will be determined by the type of space heating (or cooling) application the heat is used for, the temperature of the heat source, and the temperature of the demand-side distribution system. There are practical limitations imposed by the storage container as well: a greater temperature difference between the storage material and the ambient temperature will increase the rate of heat loss through the container walls, therefore increasing the need for more or better insulation.

Heating systems are often classified as *high temperature* systems or *low temperature* systems, with low-temperature systems typically storing heat below the boiling point of water (212°F). Low temperature systems can be used for space heating applications with hydronic distribution systems. For instance, baseboards require heat in the range of 150-180°F, and radiant floors require temperatures of 85-100°F. Higher temperature storage, or systems that store heat above 212°F, can be used for forced air systems: in these systems, air is often blown over rocks or ceramic bricks with stored heat. The high temperature heat storage can also be stepped down for other uses.

2.5 Size

The size of the thermal storage system will depend on several factors:

1. The application that requires heating (heat load)
2. The heat source, its BTU output capability, and firing time
3. The heat capacity of the storage material
4. The time frame of the storage
5. The expected standby loss

Optimal sizing of the thermal storage system is important to maximize the system efficiency. Without a supplemental heating source, undersized thermal storage systems are insufficient to meet heating demands. Oversized systems have a higher capital cost, can cost more to maintain, and can waste energy through standby losses. For seasonal storage systems, sizing the system is even more important as even optimally sized systems can occupy a large space and require high installation costs.

To calculate the size and design of the thermal storage system, builders must begin by calculating the heat load of the building's space heating or domestic hot water system. This is best accomplished by using residential energy modeling software such as AKWarm, DOE-2, or PHPP. In Alaska, many building professionals use AkWarm, an Alaska-based energy rating software maintained by the Alaska Housing Finance Corporation. This type of software provides users with monthly energy flows of the house in addition to the energy use of heating and cooling systems. Builders may also use the sizing methods in the *Air Conditioning Contractors of America Manual J: Load Calculations* to estimate heating and cooling loads. Using the heat load, builders can calculate how much thermal storage is needed to provide sufficient heat during the given time frame.

The next step is to ensure that the thermal storage system can provide adequate heat at the time it is needed. This depends on the expected relationship between charging and use, the heat source, the size of the thermal storage system, the heat load, and the expected standby loss. For instance, consider a storage tank connected to a wood boiler. The residents may have decided that they would only like to fire the boiler every few days. In this case, the storage material must be able to store enough heat to heat the house for the few coldest days of the year if there is no back-up heating system. A similar situation exists with solar thermal systems. If the resident aims to use the solar thermal system only during the summer months, the thermal storage system must store enough heat to meet the needs of the house if a few cloudy days occur. If the objective is to store heat from the sun year-round, the storage configuration will have to be large enough to accommodate months with limited solar resources.

Another influence on storage size is the expected standby loss. If the storage is located indoors, any standby loss that occurs will still contribute to space heat for the home. However, if the storage is located outdoors, standby loss will be a total loss. Standby loss can be minimized by locating the storage indoors, and by insulating around the storage.

Reducing the heat load of the building through energy efficiency measures will reduce the storage system size, which results in a smaller capital cost for the system. Additionally, the use of passive heating techniques in the building can reduce the heat load placed on the thermal storage system. Other systems combine multiple heat sources to heat the thermal storage. For example, solar thermal system water tanks may also contain a heat exchanger loop to pull heat from a boiler if the solar thermal panels cannot maintain the minimum useful tank temperature in the winter.

In some cases, the thermal storage system is the secondary heat source. In such residences, the thermal storage system simply offsets some of the heating load that the primary heating appliance must provide. This is popular for renewable resources that are not sufficient to provide heat for an entire house, or for waste heat that is variable in quantity. It is important in these situations to estimate the amount of heat the thermal storage system can provide, so that the primary heating system can be sized correctly.

2.6 Efficiency

In contrast to heating appliances (many of which undergo a standard test to determine a seasonal efficiency, such as AFUE for boilers and furnaces and COP for heat pumps), there is no industry standard for the efficiency of a thermal storage system. The U.S. Department of Energy provides a method for measuring the efficiency (called the Energy Factor) of storage water heaters. The Energy Factor allows comparison across water heaters and encompasses both standby losses and inefficiencies associated with the heating mechanism (such as the heat lost up the flue in combustion systems).

The system efficiency of a thermal storage system encompasses several components. First, there are inefficiencies associated with the heat source. Solar thermal panels, wood boilers, electrical plants, and wind turbines all have inefficiencies associated with their operation. Additionally, heat is lost when being transmitted to the heat storage system. Transmission loss occurs again when the heat is discharged to the distribution system.

Also, all thermal storage systems will experience standby heating loss. The standby loss refers to the heat lost through the container walls. In the case of storage with no “container,” such as heat storage in the ground or an underground aquifer, the standby loss is the heat lost to the surrounding area. Standby loss is mitigated in man-made containers by minimizing the surface area of the storage container and increasing the amount of insulation around it. Greater temperature differences between the storage material and the surrounding area increase the rate of heat loss. There is also heat lost from piping and ducting carrying heat-transfer fluid to and from the storage unit. This loss can be minimized by insulating the piping or ducts, and running them through conditioned space.

Standby losses can be useful during the heating season if the storage container is located in a conditioned area. However, in this case, the additional heat will contribute to the cooling load of the residence during the summer months. For short-term storage systems, standby losses are not as important, as the system can recharge often.

They do need to be prevented to the extent possible for long-term seasonal storage, however, because in the winter less heat may be available for charging (Dincer & Rosen, 2011).

2.7 Retrofit and new construction considerations

New construction offers considerably more flexibility for designing a thermal storage system, because the system does not have to fit within a pre-existing space or distribution system. The space is a major consideration, as many systems involve high-volume containers (such as 5,000 gallons). Builders must also consider how standby losses will affect the area around the storage container. In new construction, the storage container can be located indoors, where standby losses can contribute to the building's heat supply (in states such as Alaska, where many locations have 10-12 months of space-heating demand, this can be helpful).

Certain storage materials can be divided and separated, which can make retrofitting easier; basically, the storage materials can be carried through existing doors and assembled together indoors. For instance, ceramic bricks used for heat storage are modular and available in various sizes. They can be carried individually into a room and assembled together inside an insulated container, which contains a fan to distribute heat to the room (Dincer & Rosen, 2011). This method was recently implemented in southwest Alaska in the Chaninik Wind for Heat Pilot Project (Schworer, Fay, & Meiners, 2011). Another way to add thermal storage to an existing structure is to locate the storage tank outside of the original building, in a separate building addition or in the ground. At the CCHRC Research and Testing Facility in Fairbanks, a small addition was built to accommodate a storage tank (see Appendix B for more information). Yet another option is to buy a flexible storage tank. These tanks are shipped in pieces, designed to fit through a door, and are commercially available through companies such as Hydroflex Systems, Inc.™ Additionally, some PCMs have retrofit potential because of their high densities and modular packaging; however, PCMs are still in the research and development phase and their commercial availability is limited.

2.8 Commercialization of thermal storage

While there are residential thermal storage systems in existence throughout the world, there is not a high level of commercialization. There is no industry support group and few educational materials in comparison to other heating systems, many of which have certification programs, training programs, and promotional materials from a centralized group. The lack of information on thermal storage, the lack of commercial options for installing a thermal storage system, the capital cost of systems, and the infrastructure constraints (such as limited space in buildings being retrofitted) are some of the barriers to widespread adoption of thermal storage (Dincer & Rosen, 2011).

ASHRAE provides a couple of standards for testing thermal storage systems (Dincer & Rosen, 2011): Standard 943 "Method of Testing Active Sensible TES Devices Based on Thermal Performance" and ANSI/ASHRAE 94.1-1985 "Method of Testing Active Latent Heat Storage Devices Based on Thermal Performance." However, there are no requirements that systems be tested to these standards. Additionally, many systems are highly customized, so comparison is difficult. However, ongoing research throughout the world on thermal storage systems is helping push the systems forward. Such research has focused on addressing technical issues, improving performance, developing new storage materials, making systems more compact, and analyzing heat transfer (Dincer & Dost, 1996).

Several builders in Alaska are currently installing thermal storage systems; Appendix B of this report contains case studies of cold climate thermal storage systems, many of which are located in Alaska. Each system is unique and tailored especially to the constraints of the residence, as there is no common standard for implementing cold climate thermal storage systems. However, general building techniques are spreading through the state's closely connected building community through conference presentations and small meetings as public interest grows in Alaska. The Cold Climate Housing Research Center is currently in the planning stages of a thermal storage demonstration project for a building addition set to open in 2013. The system will be monitored and subjected to a life cycle cost analysis. It should increase public awareness of thermal storage systems, and also provide a system for builders and researchers to evaluate. More information can be found at cchrc.org.

3. Thermal Storage Examples

While there is a great amount of variety in types of thermal storage systems, there are some system designs that have been implemented more frequently than others. These are discussed below, and are organized by heat source. For specific examples and descriptions of thermal storage systems in cold climates, please see Appendix B.

3.1 Electrical thermal storage (ETS)

ETS refers to the process of converting electricity to thermal energy and storing it as heat. This certainly is not practical in areas with electrical shortages or high-priced electricity, but is useful for areas with low-priced off-peak power or for providing additional grid load for intermittent resources like wind. For example, when the wind is blowing but there is not sufficient electrical demand to balance grid loads, the electricity is converted to heat by an electric heating element. Heat can be placed in several types of storage materials, but is typically stored in high-density ceramic bricks with an electrical heating element at their core. The bricks are stored in insulated cabinets to minimize standby heat loss. One advantage of these systems is the fact that there is no combustion, and thus no concerns about carbon monoxide or other combustion byproducts. Non-combustion systems also require very little maintenance. Also, the bricks' high density means that the cabinets of bricks are not large, but can weigh hundreds of pounds. In some cases, water tanks are used for the same purpose in balancing electrical loads.

ETS systems can be charged with off-peak power, solar, or wind electricity, or they can be used to store heat from a heat pump. The length of storage time depends on the size of the system, but generally is on the order of 6-24 hours. Off-peak grid power hours occur daily, so the systems are typically sized to take advantage of this charging time each day. Renewable systems may be sized for longer times.

Controlled heat delivery for the brick type ETS occurs through the use of fans. The fans turn on when the thermostat signals that a room needs heat. Air passes over the bricks and is heated before being blown into a room. The ceramic bricks used in ETS similarly will discharge heat slowly over time through the container walls through standby loss. However, the "lost" heat goes into the room being heated, so it is not a total loss. Heat delivery in water tank type ETS is controlled through hot water consumption.

ETS systems are highly versatile. They can be sized to heat a room, or multiple units can be installed to heat a house. They work well for retrofits and new construction because they are modular in size and easy to install.

3.2 Biomass technologies

Wood boilers are a type of hydronic heater that burn wood to heat a fluid, typically water. With a hydronic distribution system, heat can be sent to various places in a house. Heat can also be delivered to a thermal storage system, such as an insulated tank of water, which decouples the house heat demand from the combustion process.

The volume of thermal storage for a wood boiler is similarly determined by examining the time frame of storage, the heat load, the storage material, the expected standby loss, and the BTU output of the heat source. An additional consideration for wood boilers is that being able to operate the boiler at full load (a hot fire) is more efficient than operating it at partial load (a damped down fire that is smoldering). A large volume of storage thus offers the advantage that the boiler can always be operated at full load (resulting in lower combustion emissions). It also means that a single combustion period will cover a larger time period of heat demand. However, smaller volume storage offers lower capital costs and lower standby heat losses. Ideally, the size will be determined by optimizing cost and boiler performance (Bioenergy2020 + GMBH, 2010).

Hydronic heaters stand to gain much more from thermal storage than simply an increase in homeowner convenience. Outdoor wood boiler systems can increase their efficiency by using thermal storage. Heating a tank of water allows the boiler to run for a long period of time, and then shut down for a long period of time while the building draws heat from the tank. The avoidance of on/off cycling increases efficiency, thereby saving fuel and reducing airborne emissions. However, the cost of installing a thermal storage system will increase the capital cost of the heating system.

Hydronic heaters are not currently regulated by the EPA, although the EPA does maintain voluntary emissions standards for hydronic heaters. They do produce emissions such as carbon monoxide, nitrogen oxide, and particulate matter. The EPA maintains a list of clean-burning hydronic heaters on its website. However, even clean-burning hydronic heaters can produce excessive emissions when combustion air is severely restricted (the boiler is “damped down”) to produce less heat. Letting a fire smolder reduces efficiency and increases pollution (CMHC, 2008). Thermal storage systems allow wood boilers to burn hot fires without having to damp down the flames, since extra heat can be stored in the storage system and used later.

3.3 Solar thermal systems

Solar thermal energy has several advantages: it is a renewable resource, requires no transportation, and does not have the price volatility of other fuels. It can be especially viable in well-insulated houses with small heating loads, even in Alaska. However, solar thermal systems must overcome a mismatch between supply and demand, on both daily and seasonal scales. Heat is needed during the winter, when sunlight is at a minimum, and at night, when the sun is not available at all. Thermal storage can be used to smooth out this discrepancy.

In solar thermal systems, solar radiation is converted to heat by flat plate collectors. Inside the collector, a fluid absorbs the heat that has been absorbed by the collector. In cold climates, the fluid should have a low freezing point and the system should have freeze protection measures in place.

Systems exist on several scales. Smaller scale systems can meet heating demands overnight or for a few cloudy days. Typically, they store heat for time periods less than one week. The heat can be stored in buffer tanks of water, or even in the building’s thermal mass for daily cycles. Smaller-scale systems have moderate capital costs and can be located indoors. Larger-scale systems offer seasonal storage (they can store heat for 3-4 months), but require large space and higher capital cost. A large-scale system can be used in a district heating system, or a heating system designed to provide space heating to multiple houses. Larger-scale seasonal storage offers several advantages, though. It reduces the need for a back-up heating system, since a few cloudy days do not have much effect over the course of a year, and allows the collector area to be reduced, which in turn minimizes collector stagnation during the summer (Dincer & Dost, 1996). Another advantage to large-scale seasonal storage is a higher volume-to-surface area ratio, which reduces the standby loss compared to containers with smaller volume-to-surface area ratios (Novo, Bayon, Castro-Freson, & Rodriguez-Hernandez, 2010). Storage for heating large districts, instead of a single building, can be more cost-effective for this reason. They can be designed to cover all or part of the heating needs of a community.

In Alaska, seasonal storage for the winter months requires a substantial amount of volume. *The Solar Design Manual for Alaska* (Seifert, 2010) estimates that the volume of water needed to store solar thermal heat for a well-insulated house during the four coldest and darkest months (November–February) could be up to 31×31×8 ft^3, which is the equivalent of over 50,000 gallons, or the size of a large room. Recent builders, however, have combined solar thermal systems with much smaller thermal storage tanks. The smaller sized tanks (5,000 gallons or less) are enabled by a few factors. First, the houses are super-insulated so that the heat load is minimized. Secondly, secondary heat sources such as masonry heaters are used as a back-up source of heat for the storage tank during the cold winter months. This allows for lower-volume thermal storage, since firing the masonry heater can provide heat to the thermal storage when its temperature drops. Lastly, stratification of the thermal storage fluid allows the hot water at the top to be drawn off for use in the distribution system, even while the entire tank is not hot enough for distribution.

For short-term storage, water is a common medium for solar thermal systems because of its low cost, high heat capacity, and ability to stratify. Disadvantages to using water are that it can require a large volume for seasonal storage, and containers can leak. Rock and ground storage are other common choices, especially for higher temperatures. For a given heat capacity, rocks require more volume than water. However, they are less expensive to install and maintain than a liquid storage system and can be used with forced air systems. Rock storage systems can even be stratified, with higher temperatures at the top than at the bottom of the storage container. To enable stratification, heated air must be transferred to the storage container at the top, and then move downward towards the lower temperatures. Ground storage requires drilling or excavation to install heat exchangers, but it does not take up space within the interior of the house. Also, ground storage may not be an option in areas with soil with low groundwater content because of the soil's low thermal conductivity.

Seasonal storage of solar thermal energy has been researched since the 1960s (Novo, Bayon, Castro-Freson, & Rodriguez-Hernandez, 2010). Research includes demonstration projects, development of new storage technologies, improving existing strategies to be more efficient and store heat longer, and development of simulation tools to aid in design. Future research is expected to develop storage materials (Novo, Bayon, Castro-Freson, & Rodriguez-Hernandez, 2010). Currently, there are five main storage types used for seasonal storage (Novo, Bayon, Castro-Freson, & Rodriguez-Hernandez, 2010) and (Pinel, Cruickshank, Beausoleil-Morrison, & Wills, 2011). They are listed below. All options are listed for completeness, but some are more suited to cold climates than others.

1. Aquifer thermal energy storage: Thermal energy is transferred by pumping groundwater out of the natural aquifer (extraction well), extracting heat from the water, and then re-injecting the lower-temperature water into a separate (injection) well. Aquifers are found throughout the world, and can be used as sources of fresh water. The amount of heat that can be stored in one depends on the allowable temperature change, the thermal conductivity of the aquifer, and the groundwater flow.
2. Borehole thermal energy storage: Vertical heat exchangers carry fluid to transfer thermal energy to and from soil. Heat is stored in the ground and is extracted by heat exchangers when needed. Many

boreholes are used in combination with ground source heat pumps. Ideally, boreholes are drilled in soils with high conductivity, such as rocky soils or soils with high water content.

3. Pit storage: Also known as man-made aquifers, pit storage is an artificial structure designed to hold water and rocks or gravel for thermal storage. The pit is buried in the ground, lined with watertight plastic, and insulated on the sides and top. Pit storage is typically less expensive than a water tank, but requires more volume for the same amount of thermal storage because the specific heat capacity of rocks and water is less than that of water alone.
4. Solar pond: Either natural ponds or man-made ponds can be used in warmer climates. In a typical pond, warm water is less dense than cold water, so it rises and loses heat to the atmosphere. In a man-made solar pond, a salt solution can be added to the bottom of the pond. The denser water then stays at the bottom, even when warm. The sun warms the top of the pond, and a heat exchanger is added to the bottom of the pond. The salt solution can be added to the water in the pond to inhibit natural convection and trap heat at the bottom of the pond. These ponds require some maintenance to control algae growth, so water remains clear and sunlight can penetrate. Ponds with a dark bottom will absorb more radiation. These are used in warmer climates that do not get snow.
5. Water tanks: Water tanks consist of insulated containers, often buried or located inside a building, to hold water for thermal storage. An advantage of water tanks is that they can be built independent of geological conditions, are relatively simple to insulate, and can be charged and discharged with water flow.

The installation of any one type depends on the geological and hydrogeological conditions of a site. Systems can also incorporate more than one type of storage. For example, rock and water storage can be combined in tanks of both rock and water, or a water tank surrounded by rocks. Another example consists of both a buffer tank of water for short-term storage, and then boreholes for long-term storage in the ground.

Another use for solar thermal systems is in combination with a ground loop and ground source heat pump. The solar panels can be used to provide heat to a distribution system for space heating, or to a thermal storage tank. During times when the solar thermal heat is not needed for domestic applications, heated fluid from the solar panels can be circulated through ground loop. The solar thermal heat can help replenish the heat taken from the ground by the ground source heat pump. The ground can also act as additional “thermal storage” since the heat from the solar panels raises the temperature of the soil. For heating-dominated climates, sending heat from solar panels to the ground over the course of the year helps to balance the amount of heat taken from the ground in the winter by the heat pump. One such system, described in Wang, Qi, Wang, & Zhao (2009), uses solar thermal panels, a 211-gallon indoor tank, a ground loop in the soil outside the building, and a heat pump. The solar panels are meant to improve the energy efficiency of the system and prevent the ground temperature from decreasing over time. There is a similar system located in Fairbanks, Alaska at Weller Elementary School. Solar panels and a ground source heat pump at the school provide heat to a water tank in the building. During the summer season, heat from the solar panels is used to replenish heat in the soil around the ground loop.

Synthesis of Findings

This section consists of the key findings drawn from interviews with builders and owners of thermal storage systems, and a literature review of thermal storage. The findings here apply to thermal storage systems in general, but are written specifically for thermal storage systems in cold climates.

Thermal storage is not a heat source in itself, but rather a means to store heat energy for controlled use at a later time. Sensible thermal storage is overwhelmingly the type currently being implemented.

Simply stated, thermal storage acts like a "heat battery" by allowing for the controlled charging and discharging of a medium with heat energy. While there are three types of thermal storage (chemical, sensible, and latent), sensible storage is overwhelmingly the type being installed in residences today.

Thermal storage can enhance the use of renewable energy resources, such as the use of solar thermal space heating systems, by storing heat to fix the mismatch between the supply and demand of energy.

Homeowners, including those located in cold climates, have used functional thermal storage systems to store solar thermal energy until it can be used. These systems exist on a wide variety of scales: from storage meant to store solar heat overnight for a single home to storage designed to run a neighborhood heating system through the winter season. A number of publications document and describe existing systems (see Appendix A), some of which have been in use for several years. In cold climates, they have all implemented a secondary heat source (such as wood energy) to charge the thermal storage during the coldest months.

Thermal storage can increase the efficiency and reduce the operating cost of heating systems.

Thermal storage has the potential to increase the efficiency of certain types of heating systems, such as wood boilers and ground source heat pumps, by reducing cycling. For instance, a storage tank can allow longer burn times for a wood boiler, resulting in more efficient operation and fewer emissions. Ground source heat pumps with buffer tanks can also increase efficiency and reduce machine wear-and-tear by allowing longer and fewer run times. Of course, the final system efficiency will depend on the specific system design and amount of standby loss. Thermal storage can also potentially lower operating costs by enabling the use of electricity during off-peak rate periods, if and when offered by the utility. This can reduce costs for heating systems with a significant electrical power draw (such as heat pumps) if the operating cost of the storage system itself is not so high as to negate the savings.

Seasonal thermal storage systems can be and are used in cold climates.

There are a number of operational seasonal thermal storage systems in cold climates, including many Alaska systems profiled in Appendix B. The majority of these systems are highly customized or prototype designs for residential buildings, and involve more than one type of heat source (for instance, solar and wood energy) to charge the storage during the winter. They involve many site-built storage components, such as poured concrete or modified steel tanks, and have enabled users to heat their homes with minimal or no fossil fuels. Unfortunately, limited quantitative data on the efficiency, fuel use, and cost of these systems exists.

Thermal storage systems are highly adaptable and can be used with many renewable and non-renewable heating sources.

Thermal storage systems are most suited for renewable energy systems such as solar thermal, geothermal, and cordwood biomass, but with the proper design they can be used with a wide variety of heat sources. The size of the system can also be tailored to hold heat from a few hours to an entire season. Storage materials can include water, rock, soil, and others. Homeowners can choose from a wide variety of type and size of system.

Currently, thermal storage installations, especially those in cold climates, are limited by lack of an established thermal storage commercial market together with lack of information on performance and life-cycle costs.

While several thermal storage installations exist in Alaska, as does literature on the performance of thermal storage, there is little established representation or industry focus for thermal storage. Larger thermal storage systems, especially those used for seasonal storage, are complex mechanical systems. However, there are not standardized designs or controls for such systems on the market. Additionally, there is no industry support group, few district heating networks and commercial options, and a lack of information packages on thermal storage options (Dincer & Rosen, 2011). Also lacking is information on system capital cost, performance, and lifetime maintenance costs. Most systems are unique installations that combine site-built components and non-standardized control systems. While thermal storage might be a possibility for a wide variety of homeowners, many homeowners are unaware of the option, uncertain about how to approach installing such a system, or even unsure how to find out whether it is appropriate for their home.

Research Recommendations

Using thermal storage in residential cold climate construction represents another avenue for improving heating systems in a climate with traditionally high heating costs. While there are operational thermal storage systems in cold climates, there are few rules-of-thumb regarding their installation. Furthermore, the building community currently lacks accessible resources on the types of systems that can be installed and their operational characteristics. The following recommendations are meant to complement the introductory informational text in this report. The recommendations address knowledge gaps and research needs that would advance the understanding and use of thermal storage technology in cold climate heating systems.

Life Cycle Cost Analysis on Seasonal Solar Thermal Storage Systems in Cold Climates

A life cycle cost analysis on any of a variety of systems would provide more definitive information on capital costs, maintenance costs, and potential savings from using thermal storage with a heating system. This would reduce the current uncertainty that surrounds the installation of such systems. In particular, though, seasonal solar thermal systems in cold climates represent a deviation from more common thermal storage practices, such as the use of solar thermal domestic hot water in warmer climates, and there is little available information on their performance. Additionally, as many seasonal thermal storage systems contain custom and site-built components, there is a high level of uncertainty on initial and operating costs. Currently, the case for such systems is based on using renewable energy instead of fossil fuels. A life cycle cost analysis of such a system, compared to baseline life cycle cost analyses of more common heating technologies, would provide an economic basis for a decision install a seasonal solar thermal system.

Quantitative and Qualitative Performance Data on Thermal Storage Systems in Cold Climates

In addition to a lack of cold climate-specific data on costs, there is also a lack of information on the performance of systems. There are a number of Alaska case studies, and information spreads through presentations and word-of-mouth. However, a comprehensive review with quantitative data on energy stored, length of time stored, and energy lost to standby loss or other inefficiencies is needed. Also, qualitative data on topics such as maintenance requirements, comfort levels, ease of installation and maintenance, and aesthetics will help homeowners make better decisions on installing a system. Again, it is important to have this data on a variety of different systems, so that future users of thermal storage systems could discover pros and cons of each option. Such information could also lead to system design standardization, which would help reduce errors in system design, provide more certainty on system performance, and facilitate the development of pre-packaged control systems that would simplify implementation and optimize efficiency.

PCM System in a Cold Climate

There is currently not a known system using PCM in a cold climate. As PCMs have the potential to reduce the space needed for storage when combined with another system, they could prove useful in cold climates where substantial amounts of storage are needed for seasonal storage of heat energy. Currently, PCMs are in the research and development phase. A cold climate demonstration or a partnership with an entity currently researching PCMs in a warmer climate would provide cold climate residents with some climate-specific performance characteristics should PCMs become commercially available.

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Appendix A: Literature Resources

Bauer, D., Marx, R., Nuβbicker-Lux, J., Ochs, F., Heidemann, W., Müller-Steinhagen, H. (2010). German central solar heating plants with seasonal heat storage. *Solar Energy*, *84*, pp. 612-623.

This paper describes different types of thermal energy stores used by central solar heating plants in Germany. Such seasonal heat storage combined with central solar heating plants can enable higher solar fractions. This paper compares operational characteristics from extensive monitoring programs.

Bioenergy2020+GMBH. (2010). *European Wood-Heating Technology Survey: An overview of combustion principles and the energy and emissions performance characteristics of commercially available systems in Austria, Germany, Denmark, Norway, and Sweden*. Albany: New York State Energy Research and Development Authority.

This report is meant to inform the New York State Energy Research and Development Authority and the U.S. Environmental Protection Agency of the current technology of wood boilers available in Europe. It provides information on biomass combustion, emissions, European regulations and standards, the performance of wood-burning appliances in Europe.

Bruno, F. (2004). Proceedings from Performance Enhanced Buildings Conference '04: *Using Phase Change Materials (PCMs) for Space Heating and Cooling in Buildings*. Sydney, Australia: Australian Institute of Refrigeration, Air-Conditioning, and Heating.

This paper briefly describes how PCMs work and where they can be used. It then reviews recent research and existing systems.

CMHC. (2006). Low-Impact Housing: Ketchum House 1998. Ottawa: Canada Mortgage and Housing Corporation.

This publication provides details on an energy-efficient house built in Ontario. It discusses the characteristics of the house, the local climate, and the mechanical systems. The strategies used for energy conservation are also described.

CMHC. (2006). *Solar Energy for Domestic Hot Water and Space Heating* (Better Buildings Case Study No. 60). Ottawa: Canada Mortgage and Housing Corporation.

This publication is one of a series on efficient buildings. It describes the renovation of a group of townhouses in Ottawa that installed solar thermal panels to help meet their space heating load. The solar thermal panels are used with a boiler to provide space heating and domestic hot water to units that are on a shared heating system.

CMHC. (2009). *Klosterenga – Oslo, Norway* (Innovative Building Series). Ottawa: Canada Mortgage and Housing Corporation.

Klosterenga is a residential apartment in Oslo that was built with energy-conserving strategies in mind. The 35-unit apartment utilizes high thermal mass, radiant flooring, water-conserving appliances, a greywater system and on-site composting. It's location in the middle of town gives residents access to public transportation options. It also uses passive and active solar heating systems for domestic hot water and space heating.

CMHC. (2009). *Riverdale NetZero Passive Solar Design* (Equilibrium Housing Insight). Ottawa: Canada Mortgage and Housing Corporation.

This publication provides details on the Riverdale NetZero home built in Edmonton by Habitat Studio and Workshop Ltd. It gives technical specifications on the location, windows, building envelope, and the natural lighting. It also contains lessons learned from the project and the energy savings from the project.

Davies, J., Misiuk, D., Colgan, R., & Wiltse, N. (2008). *Reducing PM2.5 Emissions from Residential Heating Sources in the Fairbanks North Star Borough: Emission Estimates, Policy Options, and Recommendations*. Fairbanks, AK: Cold Climate Housing Research Center.

This report describes the emission estimates calculated from a model that was created to estimate the baseline PM2.5 emissions from residential heating sources in Fairbanks, AK. It also covers policy options that could reduce PM2.5 emissions and includes recommendations on the which policy options will be effective, enforceable, and affordable.

Demirbas, M. (2006). Thermal Energy Storage and Phase Change Materials: An Overview. In *Energy Sources, Part B: Economics Planning and Policy* (85-95). Philadelphia: Taylor and Francis Group, LLC.

Thermal storage is like a thermal battery, used to provide energy management in buildings. This chapter reviews sensible and latent heat storage, with an emphasis to phase change materials used for latent heat storage.

Dincer, I. & Dost, S. (1996). A perspective on thermal energy storage systems for solar energy applications. *International Journal of Energy Research*, *20*, 547-557.

This article discusses several aspects of thermal storage. It begins with a description of different types of thermal storage. It then addresses the efficiency of thermal storage systems, materials that can be used for thermal storage, and factors that should be considered when deciding on a thermal storage system. These include safety, technological performance, applicability, environmental impact and cost.

Dincer, I. & Rosen, M. (2011). *Thermal Energy Storage: Systems and Applications, Second Edition*. United Kingdom: John Wiley and Sons, Ltd.

This textbook provides a comprehensive review of thermal storage systems for college students and engineers. It begins by giving the reader a background in thermodynamics and energy storage, but then covers the basics of thermal storage, sensible heat, latent heat and seasonal thermal storage. The authors provide energy and exergy analyses, a review on numerical modeling and case studies.

Dumont, R. (2007). *Factor 9 Home: A New Prairie Approach* (Innovative Buildings Series). Ottawa: Canada Mortage and Housing Corporation.

This publication details the goals for, design of, and the construction of a house located in Regina, Canada. The privately-financed house was built with the goal of producing 90% less greenhouse gases than typical homes in the area and its performance is being monitored by the Saskatchewan Research Council. The home has high insulation levels, high-performance windows, passive and active solar heating systems, ENERGY STAR appliances, and HRV, and a data-logging system.

Garg, H. (1985). An overview of design methods for solar water heating systems. *Solar & Wind Technology, 2*(2), 101-112.

This paper describes different design methods for solar water heating collectors and compares them to each other. The design methods include TRNSYS, F-chart, SOLCOST, SLR, SEU, GFL and the Φ F-chart method.

Haeseldonckx, D., Peeters, L., Helsen, L., & D'haeseleer, W. (2007). The impact of thermal storage on the operational behavior of residential CHP facilities and the overall CO_2 emissions. *Renewable and Sustainable Energy Reviews, 11*, 1227-1243.

This article discusses combined heat and power units, or cogeneration units, that are part of a system that contains a thermal storage tank. The use of thermal storage tanks can prolong the yearly operation time of a CHP and also allow more continuous operation. The article also discusses how the thermal storage unit affects the CO_2 emissions, and finds that it can reduce them.

Halawa, E. & Saman, W. (2011). Thermal performance analysis of a phase change thermal storage unit for space heating. *Renewable Energy, 36*, 259-264.

This article describes the results of a numerical study on a PCM thermal storage unit. The thermal storage unit in the model consisted of slabs contained in a duct; air is passed over the slabs to facilitate heat transfer. The dimensions of the slabs and the air flow rates could be varied in the model. Conclusions are presented on the effects of temperature differences on the phase change, air flow rates, slab thickness, air gaps between slabs, slab dimensions and natural convection.

Hamada, Y. & Fukai, J. (2005). Latent heat thermal energy storage tanks for space heating of buildings: Comparison between calculations and experiments. *Energy Conversion and Management, 46*, 3221-3235.

This article examines a three-dimensional heat transfer model which models a latent heat thermal energy storage tank. The tank, which stores ice using surplus electric power, has carbon fiber brushes to improve heat transfer rates. The ice is then used for space cooling during the day. The initial model predicted unallowable results, but a corrected version agreed with experimental results from laboratory scale tanks. It was found that the brushes reduced the cost of the tanks because less space was needed.

Heller, J., Heater, M., & Frankel, M. (2011). Sensitivity Analysis: Comparing the Impact of Design, Operation, and Tenant Behavior on Building Energy Performance. Vancouver: New Buildings Institute.

This white paper focuses on an analysis of building features. The authors chose a set of 28 operational features of buildings, and examined how each affected building energy performance. They also considered "packages," or combinations, of the characteristics to analyze their effects. The goal was provide residents with an idea of the implications of how they operate buildings, and designers an idea of how they need to communicate information about buildings to their occupants.

Huggins, R. (2010). Thermal Energy Storage. In *Energy Storage* (pp. 21-27). New York: Springer.

This chapter appears in a book that covers all types of energy storage. It covers thermal energy storage and discusses sensible heat, latent heat, phase change materials, and heat pumps.

Hugo, A., Zmeureanu, R., & Rivard, H. (2008). Proceedings from SBRN and SESCI 33rd Joint Conference: *Modelling of a Seasonal Thermal Storage System in a Residential Building*. Fredericton, NB: Solar Buildings Research Network & Solar and Sustainable Energy Society of Canada, Inc.

This article describes a solar thermal space heating and domestic hot water system. It is designed to use long-term thermal storage to enable the solar system to cover a whole year of space heating and domestic hot water needs without back-up heat. The method used to study the performance is a TRNSYS simulation model.

Kosny, J., Petrie, T., Gawin, D., Childs, P., Desjarlais, A., & Christian, J. (2001). Thermal Mass – Energy Savings Potential in Residential Buildings. Oak Ridge, Tennessee: Buildings Technology Center, ORNL.

This report discusses the energy savings that are possible with massive walls in buildings. First, the authors discuss the advantages of adding thermal mass to walls and summarize past studies. Then, they present their results from modeling four different versions of massive walls in 10 American cities.

Lilly, M. & Misuik, D. (2007). *Thermal Monitoring at the CCHRC Research and Testing Facility* (Snapshot RS 2007-2008). Fairbanks, AK: Cold Climate Housing Research Center.

This report gives a brief overview of masonry heaters and discusses the thermal monitoring that was used to research an existing heater at the CCHRC facility in Fairbanks, AK.

Misiuk, D. (2009). *Support for Developing a Sustainable Fire Load Reduction Program by Creating and Expanding Wood-Energy Enterprises* (RR 2008-01). Fairbanks, AK: Cold Climate Housing Research Center.

This document covers wood energy research done by CCHRC under the FNSB Grant UDAFF5. Research focused on wood energy in the Fairbanks North Star Borough. The report covers fuel sources, available wood-burning technologies, current regulations, particulate emissions, and economics. The wood-burning appliances studied include combined heat and power systems, masonry heaters, wood and pellet stoves and hydronic heaters.

Muruganantham, K., Phelan, P., Horwath, P., Ludlam, D., & McDonald, T. (2010). Proceedings from 4th International Conference on Energy Sustainability 2010: *Experimental investigation of a bio-based phase-change material to improve building energy performance*. Phoenix, AZ: ASME.

The authors report on an experiment to determine the energy- and cost-savings of installing a bio-based PCM with insulation in walls and ceilings. The experiment monitored the energy consumption and peak load of cooling 2 sheds in Tempe, AZ. One shed used PCM, and the other did not. Otherwise, the sheds were identical. Data, collected for one year, showed that peak load was shifted, and there was a maximum energy savings of 30%.

Novo, A., Bayon, J., Castro-Fresno, D. & Rodriguez-Hernandez, J. (2010). Review of seasonal heat storage in large basins: Water tanks and gravel-water pits. *Applied Energy, 87*, 390-397.

This article reviews technologies, and their advantages and disadvantages, used for underground thermal energy storage. The technologies include aquifer thermal energy storage, borehole thermal energy storage, pit storage and water tanks. All of these can be used in solar energy long-term storage in central solar heating systems.

Phase Change Energy Solutions. (2010). *Beyond Insulation*. Asheboro, NC: Phase Change Energy Solutions.

This publication introduces readers to BioPCM, a phase changing material that is based from organic compounds. The product is designed to be used with insulation in new construction, retrofits and temporary structures. It has the potential to reduce energy consumption, and shift peak energy demand by helping to maintain indoor temperatures through the absorption and release of latent heat.

Pinel, P., Cruickshank, C., Beausoleil-Morrison, I., & Wills, A. (2011). A review of available methods for seasonal storage of solar thermal energy in residential applications. *Renewable and Sustainable Energy Reviews, 15*, 3341-3359.

A major issue for solar thermal system is the development of an economic and reliable means of seasonal storage. This article covers methods of seasonal storage for residential-scale systems, including water tanks, aquifers, solar ponds, ground storage, and latent heat storage.

Reuss, M., Beck, M., & Müller, J. (1997). Design of a seasonal thermal energy storage in the ground. *Solar Energy, 59*(4-6), 247-257.

Ground storage for solar heating systems can be used in areas with favorable soil conditions. The model discussed in this paper calculates the heat transfer coefficient and the heat capacity of the soil. It takes into account the water content, mineral composition, density and shape of soil components. The paper also discusses a pilot plant that is used to store industrial waste heat.

Schweigler, C., Hiebler, S., Keil, C., Köbel, H., Kren, C., & Mehling, H. (2007) Low-Temperature Heat Storage for Solar Heating and Cooling Applications. *ASHRAE Transactions, 133*(1), 89-96.

This article discusses the use of PCMs in a solar heating and cooling system for a residence in Germany. The article covers the system design, modeling of annual operation, and advantages of the system.

Schmidt, T., Mangold, D., & Müller-Steinhagen, H. (2004). Central solar heating plants with seasonal storage in Germany. *Solar Energy, 76*, 165-174.

This paper describes 8 central solar heating plants with seasonal heat storage that were built in Germany with government R&D programs. It also describes the technology used for seasonal storage and covers planning and costs.

Seifert, R. (2010). *A Solar Design Manual for Alaska, 4th Edition*. Fairbanks: Cooperative Extension Service.

The Solar Design Manual contains Alaska-specific solar energy design information. First, it covers background information on solar energy. It then discusses solar energy technologies, active solar systems, passive solar systems, and solar hot water. Most importantly, it discusses the performance of solar systems in the north, and has case studies and technical notes from northern installers.

Sharma, A., Tyagi, V., Chen, C., & Buddhi, D. (2009). Review on thermal energy storage with phase change materials and applications. *Renewable and Sustainable Energy Reviews, 13*, 318-345.

This review provides an introduction to PCMs and covers their properties and classifications. It covers thermal storage systems, electrical storage and heat transfer.

Tyagi, V. & Buddhi, D. (2007). PCM thermal storage in buildings: A state of art. Renewable and *Sustainable Energy Reviews, 11*, 1146-1166.

This article reviews methods of heating and cooling buildings with PCMs. They discuss trombe walls, wallboards, shutters, building blocks and air-based systems. In addition, the authors also review heat transfer, principles of heating and cooling, and properties of PCMs.

Wang, H., Qi, C., Wang, E., & Zhao, J. (2009). A case study of underground thermal storage in a solar-ground coupled heat pump system for residential buildings. *Renewable Energy, 34*, 307-314.

This article describes a case study of a solar-ground coupled heat pump for a residential building in Tianjin, China. Tianjin has a cool climate. The system in the study consists of solar thermal panels, an indoor tank, heat pump and ground loop and data-logging equipment. The researchers collected data on the performance of the actual system, and also modeled the system to discover the effect of the storage tank size on the efficiency of the system.

Zalba, B., Marín, J., Cabeza, L., & Mehling, H. (2003). Review on thermal energy storage with phase change: materials, heat transfer analysis and applications. *Applied Thermal Engineering, 23*, 251-283.

This review covers the history of thermal energy storage with solid-liquid PCMs. It focuses on the materials, heat transfer, and applications.

Zhang, Y., Zhou, G., Lin, K., Zhang, Q., & Di, H. (2007). Application of latent heat thermal energy storage in buildings: State-of-the-art and outlook. *Building and Environment, 42*, 2197-2209.

Latent heat thermal storage is used in buildings to aid with space heating and cooling. This paper covers research on PCMs, including research on their properties, incorporation methods, heat transfer methods and thermal analyses of their use. It also discusses problems with PCM application and suggestions for future research.

Zhou, D., Zhao, C., Tian, Y. (2011). Review on thermal energy storage with phase change materials (PCMs) in building applications. *Applied Energy*, doi: 10.1016/j.apenergy.2011.08.025

This paper summarizes recent research on PCMs used for energy storage in buildings. It discusses PCM thermal properties, methods of incorporating PCMs into building materials, current applications, thermal performance and numerical simulations.

Appendix B: Thermal Storage Systems in Cold Climates

There are a great variety of thermal storage systems in use in cold climates, and currently over 100 systems in Alaska. The systems described below are meant to represent the different types of systems, some common and some not, located in cold climates.

Wood boiler thermal storage for daily cycling

Location: CCHRC's Research and Testing Facility in Fairbanks, AK

Building type: Commercial office building and lab

Status: Operational and used since 2010

System Description: This system was built to improve the efficiency of a wood-fired boiler located in a building laboratory addition space. Another project goal was to continue to heat laboratory space during nights and weekends when no one was in the building. The thermal storage consists of 1,500-gallon tank of water that was built into a small room that was previously added onto a laboratory. The tank shares a wall and concrete floor with the addition. The walls of the tank are reinforced ICF walls, and covered with a high-temperature liner to keep the water from leaking. Typically, the wood-fired boiler is used to heat the water to 180°F. Safety controls shut down the boiler if the temperature of the water exceeds the design limit of the tank liner. The heated water is used to provide space heating for a 1900 ft^2 laboratory space in the building through a distribution system of fans blowing air over coils of the hot water. As a backup, an oil-fired boiler heats the same space and is typically used on the weekends during cold spells when no one is in the building to fire the wood boiler. The storage tank is also occasionally used to heat a separate, smaller tank of water connected to distribution systems elsewhere in the building. However, the main use of the large storage tank is to provide heat for the laboratory space.

Figure 4: CCHRC's wood-fired boiler sits next to a 1500 gallon storage tank of water.

The size of the tank was determined based on how hot the water would be, and how many BTUs would be produced with one firing of the wood boiler. Researchers measured how much wood could be burned in the firebox, and calculated how many BTUs the wood could produce. The tank was made large enough to allow for one firing of the boiler per day, if the water were to reach 180°F, and to be large enough to provide heat to the laboratory over the course of 24 hours during the winter (with the knowledge that the back-up oil-fired boiler would provide supplemental heat if needed).

Improvements have been made to the system since it was installed to improve its efficiency. The original boiler used a draft damper to control the fire in the firebox. A flue gas analyzer test on the original boiler showed that the carbon monoxide content of the flue gases was higher than desired, especially when the fire was damped down as the temperature of the water in the tank approached the cut-off point. The boiler was replaced with one that has a variable speed fan that is capable of idling down the heat sent to the tank while emissions remain low. When the boiler was replaced, a larger heat exchanger was installed between the tank and the boiler, allowing more heat from the boiler to transfer into the water tank in one cycle.

Contact: Dave Shippey, Building Manager, CCHRC

Seasonal storage of solar and wood energy in Fairbanks

Location: Fairbanks

Building type: Homes (2)

Status of system 1: Operational since Fall 2010

System 1 Description: This system was built in a super-insulated house that uses multiple passive solar heating strategies. Its main component is a 5,000-gallon tank heated by solar thermal panels and a masonry heater. The tank is located in the center of a 2-story, 2,300 ft^2 house and is the main heat source for the heat distribution system. The heat exchanger for charging the storage tank of water is uniquely designed to place heated water at a depth designed to maintain stratification in the tank. It consists of two pipes: an inner pipe that contains the incoming hot water surrounded by an outer pipe with holes throughout it to reduce water velocity (see figure 7). The inner pipe has T-outlets to allow the hot water to exit horizontally into the space between the pipes. The hot water then flows into the tank through the holes in the outer pipe, entering at a depth corresponding to its temperature.

Figure 5: A 5000 gallon tank sits in the middle of a home heated by a solar thermal system. Photo courtesy Reina, LLC.

Status of system 2: Operation since Fall 2011

System 2 description: The same builder has also created thermal storage systems with external tanks for homes that cannot accommodate such a large tank within the living space. While this means that all standby losses will not contribute to the home heating, it does allow for a smaller home footprint. In one such home, the tank is heated by the same system described above, solar thermal panels and a masonry heater. A propane heater serves as the back-up heating system. In this case, however, the smaller 1,500-gallon tank is located under the 1,900 ft^2 home's foundation. The concrete foundation is poured over the tank, except for a manhole that is covered by a foam lid. The tank has sides made of 12-inch EPS foam and a 60 mm liner that was custom-made for around $1,000 and a bituthene exterior liner to prevent moisture from forming. The cost for the foam and bituthene was just under $1,000, making this tank approximately the same price as an uninsulated water tank of the same size.

Figure 6: A man-hole looks down into a 1500-gallon tank under construction underneath a house foundation.

Manager: Thorsten Chlupp of REINA, LLC

Website: http://www.reina-llc.com/

Figure 7: Heat exchangers inside a custom built tank transfer heat to the water in the storage tank. The copper coils transfer heat from the masonry heater, and the white piping transfers heat from the solar thermal panels. The white pipe is perforated to place heated water at a depth in line with the tank's stratification. Photo courtesy of REINA, LLC.

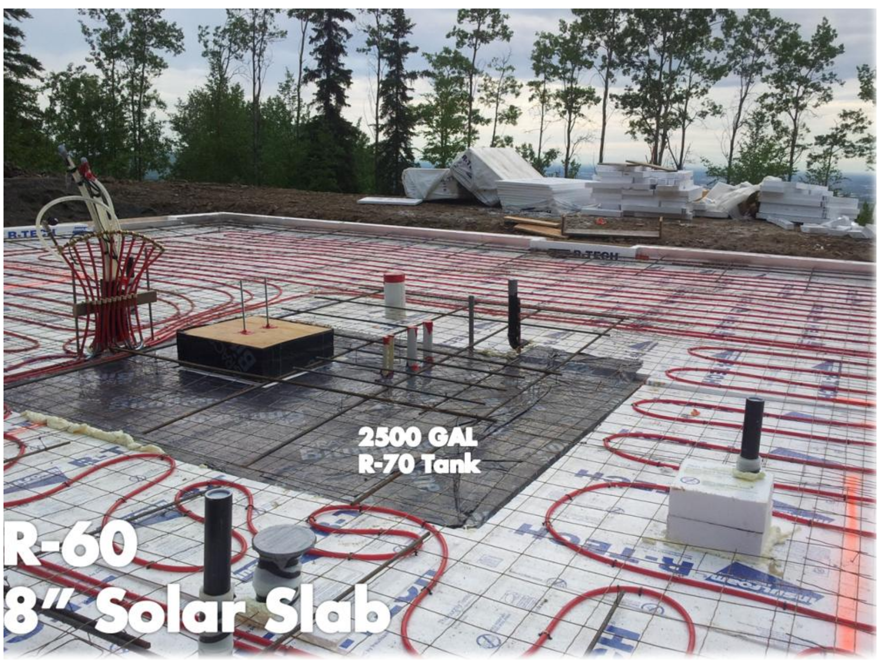


Figure 8: Foundation of a home with a tank located underneath. Photo courtesy of REINA, LLC.

Seasonal storage of solar and wood energy in Homer

Location: Homer, AK

Building type: Home

System Description: This home consists of two stand-alone buildings located next to each other. One is a house originally located on the property, and the other is an addition consisting of a greenhouse, storage space, and guest room. The original building was heated using wood and propane. When the addition was built, the owners wanted to reduce their fossil fuel consumption and installed a solar thermal system.

The solar thermal system consists of two arrays of solar thermal panels, a 6,000-gallon thermal storage tank, a 250-gallon domestic hot water tank, and a wood boiler that is used for supplemental heat during the months with little sunshine. The large tank is used to provide heat to a radiant floor distribution system. One array consists of 12 panels, and is used to provide heat to the larger storage tank. The other array has 8 panels, and is used to heat the domestic hot water tank. If the domestic hot water tank is up to temperature, the 8-panel array provides heat to the large tank.

The 6,000-gallon tank is located underneath the floor of the newer building. It was made of poured concrete and has a high-temperature liner. The tank is shallow, only 3.5 feet deep, and 28 feet long. For this reason, it experiences little stratification. Typically, the tank is kept around 170°F. The dimensions and size of the tank were mainly determined by available space. In other houses, the homeowner recommends trying to find space for a vertical tank that would allow for stratification of the water.

The solar thermal panels are sufficient to keep the storage tank up to temperature from mid-February to mid-October each year. During the darker months, a wood boiler is used to supplement the heat flow to the tanks. It is fired approximately every other day during December and January, and much less often in November and February.

Homeowner: Scott Waterman

Off-peak power use of a ground source heat pump

Location: Willow, AK

Building type: Homes (3)

Status: Operational and in use since 2008

System Description: In these homes, a ground source heat pump heats water in a 120-gallon tank during off-peak power periods in the Matanuska Electric Association area to take advantage of discounted power rates. The off-peak periods occur twice daily, once in the afternoon and again in the late night/early morning. The water tanks, charged during these two times each day, are used to provide heat to the radiant floor distribution systems in the houses. Each house is designed to have thermal mass (for instance, in the form of concrete floors) in order to help maintain the temperature of the house for longer periods of time. The sizing of the tanks was an estimate, and the installers now believe a larger tank would have been a better choice for the houses to maintain indoor temperatures during the on-peak hours.

To qualify for off-peak power rates, the Matanuska Electric Association required home dimensions, a description of the heating systems, a description of the amount of thermal storage in the home (both the storage tank and construction materials, such as concrete), and the temperature ranges that the system was designed to keep the house at. The heat pumps receive electricity through a separate meter that allows them to receive power during off-peak hours for a discounted rate. Currently, this particular off-peak power program is reviewed yearly for consideration of continuation. However, off-peak power discounted rates are common in many areas of the United States.

Manager: Walter Adolphs, Advanced Energy Systems

Electric grid stabilization through the use of thermal storage

Location: Villages of Tuntutuliak, Kongiganak, Kwigillingok, and Kipnuk in the Yukon-Kuskokwim Region

Building type: Homes (20)

Status: Chaninik Wind Group formed in 2005, system has been operational since 2011

System Description: The goal of the Chaninik Wind for Heat Pilot Project is to reduce dependency on fossil fuels, lower energy costs, and foster economic opportunities for the four villages involved. The wind energy should replace some of the diesel that the villages currently use for electricity and space heating. Additionally, the project aims to provide new skills regionally, by training local residents to maintain and operate the wind turbine system.

Figure 9: Local wind turbines provide electricity for heating in the Chaninik Wind for Heat Project. Photo courtesy of the UAA Institute for Social and Economic Research.

Homes that are involved in the project utilize electrical thermal storage ceramic bricks housed in insulated cabinets located in individual rooms. Electrical heating elements inside the brick convert power into heat, which can be stored in the bricks for up to 8 hours, and is distributed to rooms by a fan when needed. The homes in this project are using Steffes heaters (model 2106) with custom 6.0 kW heating elements (http://www.steffes.com/off-peak-heating/room-units.html) for the electrical thermal storage. The electricity is provided by wind turbines.

Manager: Chaninik Wind Group

More information: See the chapter on the Chaninik Wind Group by Tobias Schwörer, Ginny Fay, and Dennis Meiners in The Cool 100 Book (Haselip, J. and Pointing, D., 2011 *The Cool 100 Book*, Denmark: Technical University of Denmark)

Solar thermal storage with water tank and soil

Location: Juneau, AK

Building type: Homes (2)

Status: Operational and in use since September 2012

System Description: These homes incorporate a unique thermal storage system in order to enable solar thermal heat and reduce the use of fossil fuels for space heating. The thermal storage system contains two heat sources (solar thermal panels and an oil-fired boiler) and two storage mechanisms (a container of soil and a water tank). The 80-gallon storage water tank with a temperature of 180°F serves as the connection between heating appliances and the distribution system for space heating and domestic hot water.

When the the water storage tank needs heat, it can seek it from three different locations. First, it calls for heat from solar flat plate collectors. If the solar panels cannot provide sufficient heat, the water tank can obtain heat from a large volume of heated soil located nearby. A pump is used to transfer heat from coils located in the heated soil to the water. The heated soil is kept in an insulated container made from 4 inches thick rigid foam. It obtains heat from the solar panels during periods when excess heat is available, such as during the summer. Finally, if neither the solar panels nor the heated soil can provide heat to the water tank, an oil-fired boiler comes on to heat the water in the tanks.

The heating systems and water tanks were sized using estimates of the heat load of the house from AKWarm, energy-rating software produced and maintained by the Alaska Housing Finance Corporation. The dimensions of the soil storage areas were determined during construction, when builders considered the volume that was available. Currently, the soil is damp, as higher soil moisture content increases the total heat capacity of the storage system. The soil moisture content is one variable the builder is considering changing in the future to optimize the systems.

Manager: Alan Wilson, Alaska Renovators

District solar thermal heating system

Location: Okotoks, Alberta, Canada

Building type: Neighborhood of 52 homes

Status: Operational and in use since 2007

System Description: The Drake Landing Solar Community is a planned neighborhood of 52 energy efficient homes and a solar heating system that stores solar energy underground during the summer to use for heating in the winter. The solar heating system is designed to meet 90% of the heating demand. The solar energy is collected by 800 solar thermal panels that are mounted on neighborhood garages and connected by an insulated piping collector loop located mostly underground in a buried trench system. The pipes converge on an “Energy Centre,” which contains short-term water storage tanks and connections to ground thermal storage. The water storage tanks provide a connection between the long-term ground heat storage, the solar collectors, and the distribution system that brings heat to the houses (see Figure 10). The two short-term water storage tanks are 12 feet in diameter and 36 feet long. They have stratified water temperatures to improve their performance. The ground thermal storage system consists of 144 boreholes with single u-tube heat exchangers that extend to 120 feet deep. The heated water warms the soil around the boreholes. On top, the borefield is covered with sand and insulation. It is located beneath the corner of a neighborhood park.

There is a district heating loop that transfers heat from the short-term storage tank to the distribution systems in the homes. Each home is connected to the short-term storage via a two-pipe system carrying supply and return fluid. Inside the homes, an air handler supplies forced air heating from the heated fluid. During the winter, when the short-term storage tank is not hot enough to provide heat to the district heating loop, heat is transferred from the boreholes to the storage tank. The system also has a back-up gas boiler that can be used to supplement the storage system.

Domestic hot water is provided individually to homes by 2 rooftop solar thermal panels on the homes. These panels provide heat to a storage tanks located in the homes. The back-up source of heat is a natural gas water heater.

The heating system’s performance has been monitored since it began operation in June 2007. During its five years of operation, its solar fraction, or the amount of heating provided by the sun, has risen to beyond the original goal. The solar fractions for each year of operation are listed below (Sibbitt, et al., 2012):

Table 4: Solar fraction for district solar heating system during five years of operation

Year	Solar Fraction
1	0.55
2	0.60
3	0.80
4	0.86
5	0.97

Looking at Table 4, the solar fraction has improved considerably over the five years of operation. This is partially attributable to the gradual charging of the underground storage. The remainder of the improvement in performance is due to modifications to the system, including adding controls, increasing stratification in the storage water tanks, reducing electricity to run pumps, and others (Sibbitt, et al., 2012).

Website: http://www.dlsc.ca/

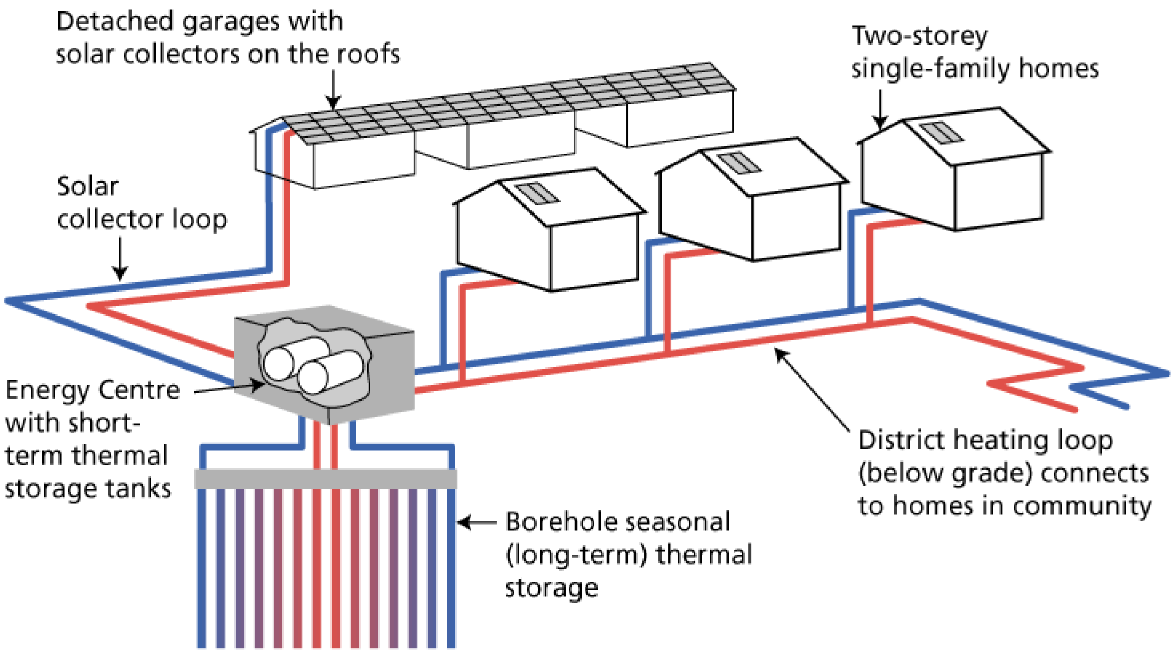


Figure 10: This diagram, courtesy of the Drake Landing Solar Community, shows the layout of the district heating system. The short-term storage tanks are an interface between long-term storage, the heating loop, and the solar panels.

Seasonal storage of solar energy in Edmonton

Location: Edmonton, Alberta, Canada

Building type: Duplex

Status: Operational and in use since 2008

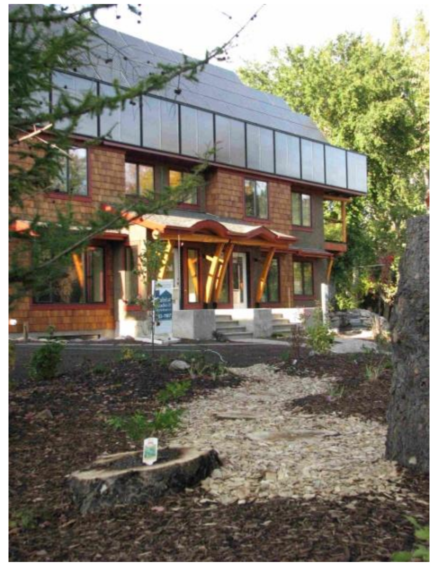


Figure 11: Net-zero energy duplex in Riverdale. Photo courtesy Peter Amerongen.

System Description: The Riverdale duplex is designed to be net-zero energy, or to produce as much energy as it uses on an annual basis. Each dwelling in the duplex is 1,773 ft^2. Located in a climate with a heating design temperature of -25.6°F, it has an energy efficient, airtight building envelope, efficient electrical appliances, a Heat Recovery Ventilator, and both solar thermal and solar photovoltaic systems. The house is heated by passive solar gain and the solar thermal system. The passive solar system employs south-facing windows and around 15,000 pounds of thermal mass in the house to store the heat. The thermal mass consists of extra mass in the walls, a masonry wall, and concrete countertops and floors. The active solar thermal system consists of solar thermal collectors, piping, a heat exchanger, a daily hot water storage tank, and a seasonal storage tank located in the basement. The heated water flows through a radiator to heat air for a forced-air distribution system, and also provides heat for the domestic hot water used by the home. There is a back-up electric heating system for both space and water heating.

The daily hot water storage tank has an 80-gallon capacity and provides domestic hot water and hot water for the space heating system. The larger 4,500-gallon seasonal storage tank is made from sealed concrete and is located in the basement. The tank floor and walls were poured with the foundation and insulated with foam board. The roof of the tank consists of fiberglass insulation, foam board, and OSB.

The system experienced some problems during the first year of use, though it is currently functioning as expected. There were water leaks and a vapor leak in the tank, air in the piping, frost damage to a collector when the drain-back system failed during cold weather, and various problems with the control system (Amerongen & Amerongen, 2011). In subsequent net-zero houses, the builders have decided to only include small solar thermal systems for domestic hot water, and use roof space for larger grid-tied solar photovoltaic systems instead of both solar PV and solar thermal, as in the Riverdale house. The builders feel that grid-tied solar PV is, in general, the better way to use roof space in colder climates, because the control system is simpler and does not require a larger storage tank to help the system through the months of little sunlight.

Builder: Habitat Studio and Workshop Ltd

Website: http://www.riverdalenetzero.ca/Home.html

Wood boiler thermal storage for multi-day heating

Location: Whitehorse, Yukon, Canada

Building type: Home

Status: Operational and in use since 2005

System Description: When he built the house, the homeowner was interested in heating with wood. After investigating wood boilers, he decided on a wood-oil combination boiler that is used to heat a 750-gallon water tank. The tank then provides heat for radiant floors and radiators in the home. The boiler, made by the Danish company Tarm, is located in an attached garage, and the storage tank is in a utility room in the house.

The homeowner burns dry wood in a hot fire when the water in the storage tank, kept at 150°F, needs heat. He will do two or three burns in a row, which typically keeps his 3,500 ft^2 house warm for two to three days during the winter. As the boiler automatically shuts off when the tank temperature is 150°F, the homeowner stops adding wood when approaching that temperature, so as to prevent the boiler from smoldering. The system is generally cleaned twice per year: once midwinter on a warmer day and once in the spring after the heating season is over. The owner uses the oil side of the boiler to heat his home in the shoulder seasons and when he is out of town.

Homeowner: Rick Farnell

Appendix C: Sample Thermal Storage Calculations

This appendix contains some sample calculations for a small solar thermal storage system that is used for providing domestic hot water. These calculations are provided to give interested readers an idea of how to do calculations for a thermal storage system. As these calculations are not meant for any specific installation, readers are encouraged to contact a heating professional if they wish to install a thermal storage system.

Tank size

In this example, we will consider the domestic hot water needs of a home where residents use approximately 60 gallons of hot water per day. If you are curious about how much water you use in a day, the Department of Energy has a worksheet for estimating water use: “Sizing a New Water Heater” at http://energy.gov/energysaver/articles/sizing-new-water-heater. Since this particular installation will use solar thermal energy to heat water, the estimated tank size will be 120 gallons, or approximately double the daily usage. This will allow the residence to have hot water, even during a period of a few cloudy days. Using 120 gallons as starting point, the following calculations will tell us whether the tank should be larger or smaller for this application.

System description

The solar thermal system will consist of solar thermal collectors that charge a 120-gallon tank used for domestic hot water during the warmer months of the year. The residence using this system is located in Fairbanks, AK. The tank will have a minimum usable temperature of 130°F (below this temperature bacteria can grow in the tank) and a maximum usable temperature of 200°F (above this temperature may result in burns for people using the hot water, even if it is first tempered with cooler water). The household is assumed to use around 60 gallons of water per day. The solar thermal collectors will be Empire EC-32 flat plate collectors, a common brand of flat plate collector.

Known constants

The following constants are necessary for the calculations:

- Heat capacity of water: 8.33 BTU/gal•°F
- 317 kWh/m^2/day (or Sun-Hrs/day) = 1 Btu/ft^2/day

System Analysis

This system will be used during the warmer months of the year. Assuming the residents want to begin using the system in April, the first step to determine how many collectors are needed is to calculate how much heat energy is needed each day.

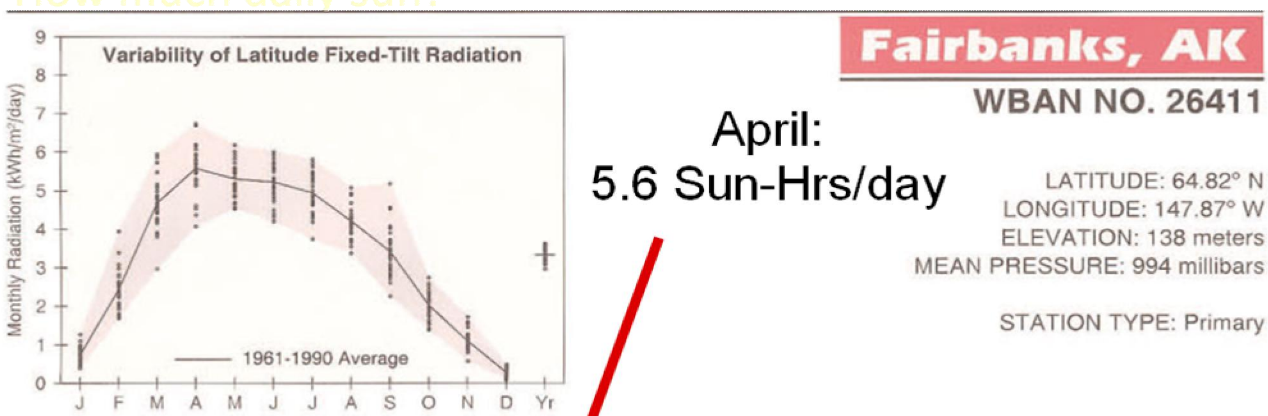
Incoming water in Alaska is around 40°F, and it must be raised to a temperature of 130°F in the tank. Since daily water usage is around 60 gallons, it will take about 45,000 BTUs of heat energy per day to heat the incoming water.

$$\Delta T = 130°F - 40°F = 90°F$$

60 gallons/day x 90°F x 8.33 BTU/gal•°F ≈ 45,000 BTU/day

The next step is to find out the average (finding the average takes into account that some days are cloudy) amount of daily heat that comes from the sun during the month of April. This depends on local latitude and climate.

This information is available online, from websites such as the National Renewable Energy Laboratory's Renewable Resource Data Center (http://www.nrel.gov/rredc/), which provides access to solar, wind, geothermal, and biomass data for locations in the United States. Below is a sample of this data for Fairbanks, AK. Assuming that the solar panels are installed at a fixed angle of 15° below the latitude angle, which optimizes the amount of solar insolation they receive during the summer months, solar panels in Fairbanks would receive an average of 5.6 Sun-Hours each day in April in Fairbanks.



Solar Radiation for Flat-Plate Collectors Facing South at a Fixed Tilt (kWh/m²/day), Uncertainty ±9%

Tilt (°)		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
0	Average	0.1	0.8	2.3	4.0	5.1	5.6	5.1	3.7	2.3	1.0	0.3	0.0	2.5
	Min/Max	0.1/0.2	0.7/0.9	1.8/2.6	3.3/4.6	4.5/5.8	4.7/6.4	4.1/5.8	3.2/4.3	1.8/2.9	0.8/1.1	0.2/0.3	0.0/0.1	2.4/2.7
Latitude -15	Average	0.7	2.2	4.5	5.6	5.7	5.7	5.4	4.5	3.4	1.9	1.0	0.2	3.4
	Min/Max	0.3/1.1	1.6/3.5	2.9/5.6	4.2/6.7	4.9/6.6	4.6/6.6	4.1/6.3	3.6/5.3	2.3/5.1	1.4/2.6	0.5/1.5	0.1/0.4	3.1/3.7
Latitude	Average	0.7	2.4	4.7	5.6	5.3	5.2	4.9	4.2	3.4	2.0	1.1	0.3	3.3
	Min/Max	0.4/1.3	1.7/3.9	3.0/5.9	4.1/6.7	4.5/6.2	4.2/6.0	3.7/5.8	3.4/5.1	2.3/5.2	1.4/2.7	0.6/1.7	0.1/0.5	3.0/3.6
Latitude +15	Average	0.8	2.5	4.7	5.3	4.6	4.5	4.3	3.8	3.2	2.0	1.1	0.3	3.1
	Min/Max	0.4/1.3	1.7/4.1	2.9/5.9	3.7/6.4	4.0/5.4	3.6/5.1	3.2/5.0	3.0/4.6	2.1/4.9	1.4/2.8	0.6/1.8	0.1/0.5	2.7/3.4
90	Average	0.8	2.5	4.5	4.9	4.1	3.9	3.7	3.3	3.0	2.0	1.1	0.3	2.8
	Min/Max	0.4/1.4	1.7/4.1	2.8/5.8	3.4/6.1	3.5/4.8	3.1/4.4	2.8/4.4	2.7/4.1	1.9/4.6	1.3/2.7	0.6/1.8	0.1/0.5	2.5/3.1

Figure 12: Solar insolation data is available online, from websites such as the Renewable Resource Data Center at http://www.nrel.gov/rredc/

Previously, we calculated how many BTUs the house would need to heat water each day. To convert from kWh/m2/day (or Sun-Hrs/day) to Btu/ft2/day, multiply by the conversion factor of 317:

5.6 Sun-Hrs/day x 317 = 1,775 BTU/ft^2•day

The next step is to determine average daily outside temperatures. Again, this data is available online, from websites such as the National Renewable Energy Laboratory's Renewable Resource Data Center (http://www.nrel.gov/rredc/).

Average Climatic Conditions

Element	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Temperature (°C)	-23.4	-19.8	-11.7	-0.7	9.2	15.4	16.9	13.8	7.5	-3.8	-16.3	-21.4	-2.8
Daily Minimum Temp	-28.1	-25.8	-18.7	-6.4	3.3	9.7	11.4	8.4	2.3	-7.7	-20.9	-26.0	-8.2
Daily Maximum Temp	-18.7	-13.8	-4.6	5.0	15.2	21.2	22.4	19.1	12.7	0.0	-11.7	-16.8	2.5
Record Minimum Temp	-51.7	-48.9	-45.[illegible]	-31.1	-18.3	-0.6	1.7	-2.8	-12.2	-32.8	-43.3	-52.2	-52.2
Record Maximum Temp	10.0	8.3	10.6	23.3	31.7	35.6	34.4	32.2	28.9	18.3	7.8	6.7	35.6
HDD, Base 18.3°C	1293	1067	930	572	282	101	68	148	325	687	1038	1232	7744
CDD, Base 18.3°C	0	0	0	0	0	14	25	7	0	0	0	0	47
Relative Humidity (%)	70	66	60	56	50	57	64	71	69	74	73	71	65
Wind Speed (m/s)	1.5	1.9	2.5	3.1	3.5	3.4	3.1	2.9	2.8	2.5	1.7	1.5	2.5

April: 5 C = 41°F
(When the sun is shining)

Figure 13: It is necessary to determine average daily outdoor temperatures to find the output of a solar panel. This data comes from the Renewable Resource Data Center.

The average climatic conditions are given in Celsius, so it is important to convert to Fahrenheit. In April, Fairbanks has an average high temperature of 41°F. Using this together with our available BTUs each day from the previous table, we can calculate the collector output. To do this, it is necessary to first find the difference in temperature between the outside temperature (T_a) and the inlet temperature (T_i) of the solar panel. Assuming the storage tank is 130°F, and that fluid goes to the inlet of the solar collector, and the outdoor temperature is 41°F, the temperature difference is 89°F.

$$(T_i - T_a): \qquad \text{April} = (130°F - 41°F) = 89°F$$

Next, visit www.solar-rating.org to look up the output of any Solar Rating & Certification Corporation (SRCC)-rated thermal collector on the market. For this, you need to know the type of collector you are installing. For this example, we assumed the Empire EC-32 flat plate collector.

CERTIFIED SOLAR COLLECTOR

SUPPLIER:
SunEarth, Inc.
8425 Almeria Avenue
Fontana, CA 92335 USA
www.sunearthinc.com

BRAND:	Empire
MODEL:	EP-32 / EP-32-0.75
COLLECTOR TYPE:	Glazed Flat Plate
CERTIFICATION #:	2007032D
Original Certification:	June 25, 2009
Expiration Date:	January 05, 2021

The solar collector listed below has been evaluated by the Solar Rating & Certification Corporation™ (SRCC™) in accordance with SRCC OG-100, Operating Guidelines and Minimum Standards for Certifying Solar Collectors, and has been certified by the SRCC. This award of certification is subject to all terms and conditions of the Program Agreement and the documents incorporated therein by reference.

COLLECTOR THERMAL PERFORMANCE RATING							
Kilowatt-hours (thermal) Per Panel Per Day				Thousands of Btu Per Panel Per Day			
Climate -> Category (Ti-Ta)	High Radiation (6.3 kWh/m².day)	Medium Radiation (4.7 kWh/m².day)	Low Radiation (3.1 kWh/m².day)	Climate -> Category (Ti-Ta)	High Radiation (2000 Btu/ft².day)	Medium Radiation (1500 Btu/ft².day)	Low Radiation (1000 Btu/ft².day)
A (-5 °C)	12.5	9.3	6.3	A (-9 °F)	42.6	31.9	21.3
B (5 °C)	11.7	8.6	5.5	B (9 °F)	39.9	29.3	18.7
C (20 °C)	10.0	7.0	3.9	C (36 °F)	34.2	23.8	13.5
D (50 °C)	5.8	3.0	0.7	D (90 °F)	19.8	10.4	2.2
E (80 °C)	1.4	0.0	0.0	E (144 °F)	4.8	0.0	0.0
A- Pool Heating (Warm Climate) B- Pool Heating (Cool Climate) C- Water Heating (Warm Climate) D- Space & Water Heating (Cool Climate) E- Commercial Hot Water & Cooling							

Figure 14: The SRCC provides performance ratings for solar thermal panels. This data is located at http://www.solar-rating.org/ratings/index.html.

Now we must use the temperature difference for April (almost 90°F), and the average solar insolation (1,775 BTU / ft2•day). The temperature of 90°F is listed in the chart, but it is necessary to interpolate to determine the solar output from the given radiation values:

Interpolate to determine output:

$$(19.8 - x)/(19.8 - 10.4) = (2000 - 1775)/(2000-1500)$$

Solving for x: $x = 15.57$

From the interpolation, each panel outputs approximately 15,570 BTU/day. As the hot water load was 45,000 BTU/day, more than one collector will be necessary. To determine how many collectors, divide the total heat load by the heat provided by each collector:

$$45{,}000 \text{ BTU/day} \div 15{,}570 \text{ BTU/day/collector} = 2.89 \text{ collectors}$$

It will take 3 collectors to meet our demand. In this case, because the goal is to provide domestic hot water even during cloudy days, let's see what 4 collectors would provide.

4 collectors chosen for additional thermal storage

Assuming 4 collectors means the system output would increase to 62,280 BTU/day. If the thermal storage system is 80% efficient (this accounts for some standby loss from the tank, heat loss from the pipes, as well as heat exchanger inefficiencies) then the system output is around 50,000 BTU/day.

15,570 BTU/day/collector x 4 collectors = 62,280 BTU/day
Assume 80% efficiency for system:
62,280 BTU/day x 80% ≈ 50,000 BTU/day

Lastly, we need to know if the tank can hold this amount of heat.

Minimum tank temperature is 130°F
Maximum tank temperature is 200°F
Temperature change, ΔT = 200°F – 130°F = 70°F
120 llons x 8.33 BTU/gal•°F x 70°F ≈ 70,000 BTU

The tank can hold 70,000 BTU. The 4 collectors can add 50,000 BTU in one day, and the daily load is 45,000 BTU. This means there is a surplus of 5,000 BTU each day during April. Assuming regular use, after 4 days, there will be a 20,000 BTU surplus, which will meet about half the DHW needs for the next cloudy day.

We now see that the tank size of 120 gallons is necessary for the system to store heat for use during cloudy days. A system with no thermal storage would require a smaller tank. However, the extra storage and extra solar panel allow this system to provide heat while the sun (the heat source) is not available.