Seasonal Solar Thermal Storage

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ABSTRACT

The purpose of this document is to explore the different methods currently available to store the sun's thermal energy during a warm season so it can be harvested later during the cold season. The solar energy is collected year round by flat plate solar collectors, and is then stored in some medium. The stored heat can be harvested later for spatial heat by moving a working fluid from a building to the heated storage medium. The two dominant storage mediums in use are the ground and large water tanks. The ground can be used by installing a borehole system for the working fluid to travel, but the ground must meet certain specifications for the whole process to be viable. If the natural ground is not suitable, then an underground storage medium can be fabricated using sand or volcanic material. Large water tanks are being used underground and on the surface. Determining the effectiveness of such storage mediums is a prerequisite before large investments can be negotiated.

INTRODUCTION AND BACKGROUND

Motivation

Data shows that space heating is a major consumer of energy which is primarily provided by the combustion of fossil fuels. Space heating accounts for 41% of all energy consumed in residential homes. In 2005 more than 97% of all homes in the United States used fossil fuels directly or electricity created from fossil fuels for space heating. Space heating in residential homes was responsible for releasing approximately 502 million metric tons of carbon dioxide into the atmosphere [EIA, 2009].

The sun provides the Earth with an average of 1000 watts per square meter of power everyday during the daytime. This is an endless amount of renewable energy that can be used for space and domestic water heating in our homes. With an increasing demand and decreasing supply of fossil fuels, it is becoming more economically justifiable to research and develop new ways of storing the sun's energy so it can be used for heating buildings. By decreasing the consumption of fossil fuels, we will also be decreasing the amount of carbon dioxide released into the atmosphere which is speculated to be a major contribution to global warming.

The purpose of this document is to explore the different methods currently available to store the sun's thermal energy during the warm season so it can be harvested later during the cold season. Storing thermal energy, or heat, from the sun for long periods of time is often referred to as seasonal solar thermal storage. Collecting thermal energy from the sun is not a new technology and has become fairly advanced and economical in recent years when the heat is used immediately. Storing enough thermal energy to provide a home with space heating for an entire winter season is a fairly new technology. Recent experiments and studies have shown that year round solar thermal collection coupled with seasonal solar thermal storage can provide anywhere from 50% to 90% of a homes annual space heating load [Schmidt, 2004]. Serious reductions in fossil fuel consumption and carbon dioxide emissions are possible using this technology. Using stored thermal energy for space heating during peak electric demand can lower the demand on the electric grid and save money. This also results in freeing high quality electric energy for industrial value adding purpose to society.

History for Single Residential Homes

The first attempt to store solar thermal energy from the summer to use in the winter was done in 1939 by the Massachusetts Institute of Technology (MIT). MIT constructed a house that later became known as the SOLAR I and tested it in Cambridge, Massachusetts. The house used 33 m^2 of pre-modern flat plate solar collectors and an insulated horizontal, cylindrical steel tank of about 63 m^3. The tank was located underneath the house in the basement beneath a floor area of about 45 m^2. Temperature of the water in the storage tank ranged from 55 ^{o}C to 90 ^{o}C. The maximum temperature was reached in August. No solar energy could be stored in the late fall and early winter since the temperature leaving the collectors was below that of the storage [Garg, 1985]. This house ultimately failed after the first season due to condensation forming in the insulation of the tank. MIT did not build another solar house using seasonal solar thermal storage until 1959 which used a smaller above ground tank that supplied water for floor radiators. The design proved to be successful after 3 years of testing and was sold to a private owner.

More recently many other colleges and universities from around the world have been competing in the solar decathlon using seasonal solar thermal storage for space heating. They are mainly using a large above ground tanks for storage and running hot water through tubes embedded in the floor, also known as radiant floor heating. These competitions have been the breeding ground for ideas of solar thermal heating. Beginning in the mid 1970's after the first major oil crisis people began adapting solar thermal storage ideas into their homes. The most common being a large above ground tank. The size of the tank needed for adequate space heating is dependent upon the size of the house, its geographic location, area of collectors, and the desired monetary investment. The optimal volume of the tank is 100 liters for every m^2 of collector area [Andersen, 2007].

In 2006 a home was constructed in Amherst, Wisconsin that uses seasonal solar thermal storage to provide for most of home's space heating requirements. The well insulated house was built on top of a 30 inch deep sand box that contains 800 tons of sand. The bottom and sides of the sand box are insulated with 2 inches of extruded polystyrene and a continuous vapor barrier. There is a 3.5 inch slab of concrete separating the first floor of the house from the top of the sand bed. There are seven 300 foot circuits of half-inch PEX tubing evenly spread out inside the sand box. The seven circuits are connected to 29.25 m^2 of flat plate solar collectors that constantly transfer heat from the sun into the sand box. During the heating season the heat from the sandbox conducts into the floor of the house sufficiently providing space heat for the entire three stories, 1,800 square foot home. The sandbox is serving as the seasonal thermal storage medium. The house is situated in a cold climate with almost 9,000 heating degree-days and only requires 1.5 cords of wood for backup heating annually [Ramlow, 2008].

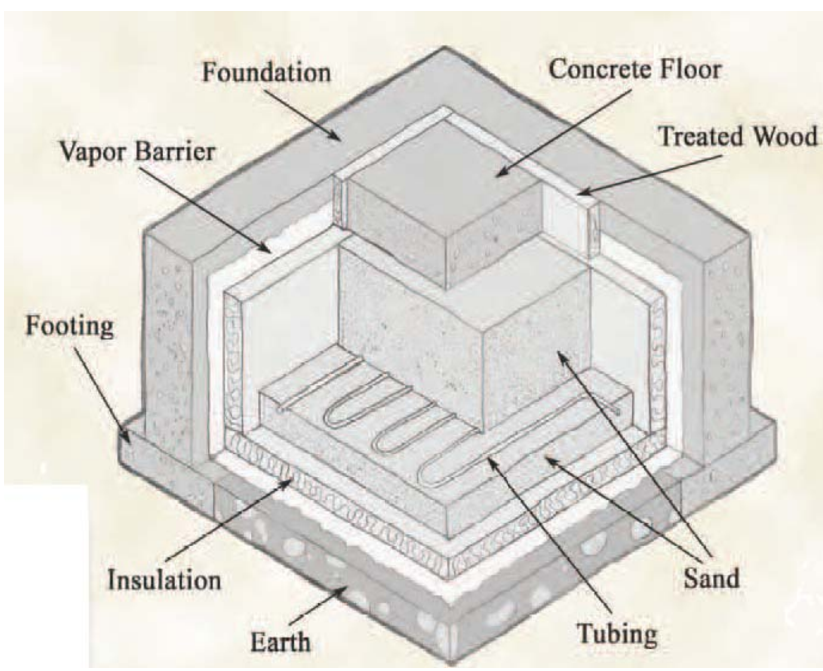

Figure 1. *Schematic of the sandbox underneath the home used for seasonal storage [Ramlow, 2008].*

History of Residential Communities

Research and development of large scale seasonal solar thermal energy storage began in northern and central Europe in the early 1980's. Sweden, Denmark, Austria, and Germany have all built large seasonal thermal energy storage projects, which aim to serve multiple buildings, homes, apartments, etc. with space heat. The first major project built was in Nykvarn, Sweden in 1985 which utilized 7500 m^2 of collector area and a 1500 m^3 water tank for storage. Throughout the rest of the 1990's and into the 21st century, several seasonal solar thermal storage projects have been built. Table 1 below lists the eleven largest European solar thermal storage projects as of 2006.

Table 1. *The eleven largest European seasonal solar thermal storage projects [Schmidt, 2004].*

Name, Country	**Year of initial operation**	**Collector area (m^2)**	**Storage type and size**	**Load size (GWh per year)**
Marstal, Denmark	1996	18,300	2100 m^3 water tank + 4000 m^3 sand water store + 10,000 m^3 water pit (to be built in 2003)	28
Kungalv, Sweeden	2000	10,000	1000 m^3 water tank	90
Nykvarn, Sweden	1985	7500	1500 m^3 water tank	30
Crailsheim, Germany	2006	7300	37,500 m^3 ground volume	N/A
Falkenberg, Sweden	1989	5500	1100 m^3 water tank	30
Neckarsulm, Germany	1999	5044	63,400 m^3 duct heat store	1.7
Aeroskoping, Denmark	1998	4900	1200 m^3 water tank	13
Rise, Denmark	2001	3575	4000 m^3 water tank	3.7
Friedrichshafen, Germany	1996	3500	12,000 m^3 water filled concrete tank	2.4
Ry, Denmark	1990	3025	Directly connected to district heating	32
Hamburg, Germany	1996	3000	4500 m^3 water filled concrete tank	1.6

The government of the Federal Republic of Germany passed laws enacting federal funding for the country to reduce carbon dioxide emissions from 1990 by 25% by the end of 2005. Space heating in private homes accounted for 30% of the total German end-use energy sector at the time, which made space heating in residential homes a huge potential for savings. The first major long term thermal energy storage was built as a research installation in 1984. Germany has built eleven large scale seasonal thermal energy storage projects since 1996 [Schmidt, 2006]. This makes Germany the world wide leader in seasonal solar thermal energy storage in terms of GWh per year and number of realized projects.

The first, and only to date, large seasonal solar thermal energy storage built in North America was Drake Landing in the town of Okotoks, Alberta, Canada. Drake Landing utilizes borehole thermal energy storage which began operation as of sunrise on June 21, 2007. Drake Landing is a solar community consisting of 52 two story, energy efficient homes. Each home has a detached garage that is connected to the neighbors garage by a breeze way and the roofs of every garage and breeze way has flat plate solar collectors installed. A total of 800– 2.45m x 1.18m flat-plate glazed collectors are currently in operation. The collectors heat a glycol solution that is circulated in a district heating system that is connected to the Energy Center. The Energy Center exchanges heat between the solar collector loop, the district heating loop, and the borehole thermal energy storage loop. Computer modeling has predicted that the Drake Landing system will be able to provide up to 90% of all space heating by the fifth year of operation when it is predicted to completely heat the 35,600 m^3 borehole thermal storage bank [Brunger, 2007]. Figure 1 below shows the basic schematic of how Drake Landing works.

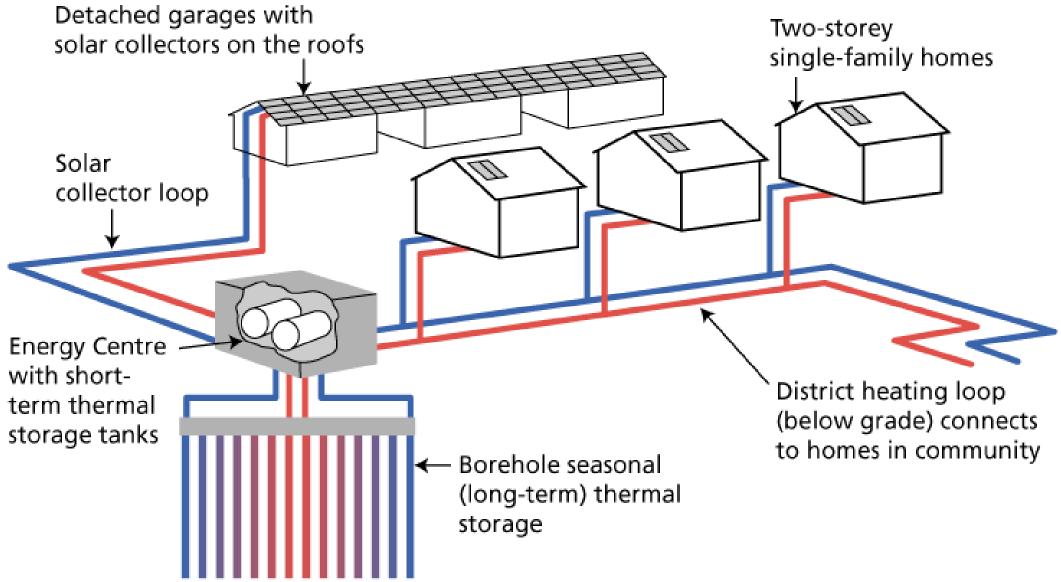

Figure 2. *Schematic of Drake Landing showing the detached garages with solar collectors, the energy center, borehole storage, and district heating loop [Drake Landing, 2009].*

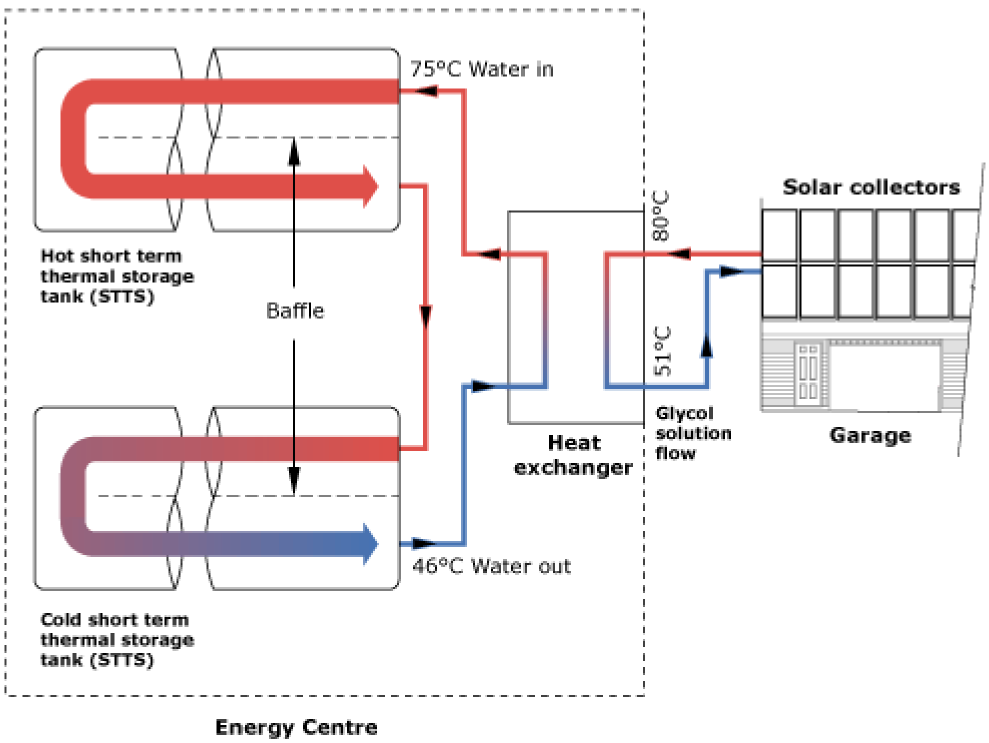

Figure 3. *Schematic of the Energy Centre heat exchanger at Drake Landing [Drake Landing, 2009].*

HOW THE TECHNOLOGY WORKS

This section of the report will mostly focus on large scale seasonal solar thermal storage that is used to heat multiple buildings or dwellings. Individual homes with seasonal solar thermal storage have either already been discussed, or exercise very similar but simpler methods as those of large seasonal solar thermal energy storage. Due to the large investment costs of this technology, it is typically more economic to practice on a large scale.

The basic overview of how seasonal solar thermal energy storage works is quite simple. Solar collectors convert light energy from the sun into heat, and they typically store the heat in a working fluid. The working fluid is typically a glycol solution to prevent it from freezing in cold conditions. The working fluid is then pumped through a storage medium directly or through a heat exchanger to transfer the heat from the working fluid to the storage medium. The storage medium can range from the ground, rocks, water, sand, or a combination of them. It is essential that the storage medium is sealed and well insulated. The majority of the heat gained by the storage medium comes during the warm season of the year, though with improving collector technology it is possible to gain significant heat during the winter season. During the winter season heat is taken out of the storage medium and delivered back to the building for space heating. The most common way in Europe to deliver the heat to the homes is via radiant floor heating while Drake Landing utilizes a heat exchanger to blow warm air through the homes' ductwork.

Water Tanks

The simplest storage medium is a large tank of water. Water is cheap, readily available, and has great thermodynamic properties such as high specific heat capacity and the high capacity rates for charging and discharging. The most common use of water tanks is above ground since it's cheaper and easier than underground water tanks. As mentioned earlier, the optimal amount of water for storage is about 100 liters per square meter of collector area. Generally water is not pumped directly from the solar collectors to the tank for two reasons. The first being that collectors generally run a glycol solution, the second being that most seasonal thermal water storage tanks are also used in combination with domestic hot water. Internal heat exchangers run the working fluid in a pipe through the inside of the tank while external heat exchangers run water out of the tank to the exchanger and then pumps warmer water back. Figure 2 shows a picture of a three different types of heat exchangers used with water tanks.

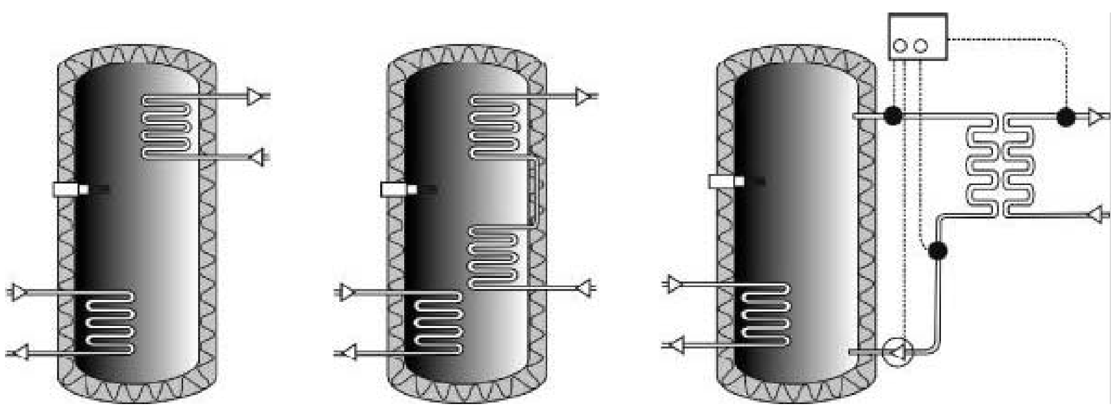

Figure 4. *The tank to the far left shows a single internal heat exchanger that can retrieve about 40% of the input thermal energy. The middle tank has two internal heat exchangers and can retrieve about 70% of the input thermal energy. The tank on the right is an external heat exchanger and can retrieve up to 80% of the input thermal energy [Nielsen, 2006].*

Large underground water tanks were the first means of storing large amounts of solar thermal energy in Europe. The largest water tank in use has a volume of 12,000 m^3

and is in Friedrichshafen, Germany. These tanks are often originally only partially underground and then the tops are covered with insulation and then earth to make them underground tanks. This type of tank is synonymous with pit storage. These tanks are unique and built on site and can be quite expensive. They are made of thick reinforced concrete with a plastic liner so that no water can touch it since cold water would hamper the tanks efficiency.

The most recent and technologically advanced underground water tank built was in Munich, Germany in 2006 at a volume of 5,700 m^3. Figure 3 shows a vertical section and the construction of the tank that was built on site. Steel liners were used as frame work during construction of the concrete walls. After the concrete walls were complete they were prestressed by steel cables, and stainless steel plates were welded together to ensure water and vapor tightness. Running vertically in the center of the tank is a stratification device to enhance temperature stratification and thereby the usability of the accumulated heat. During the springtime the solar collectors will only charge the upper part of the tank to reach usable temperatures as fast as possible. When an adequate buffer volume is created at higher temperatures, the flow from the collectors will then be switched to the bottom of the tank [Schmidt, 2006].

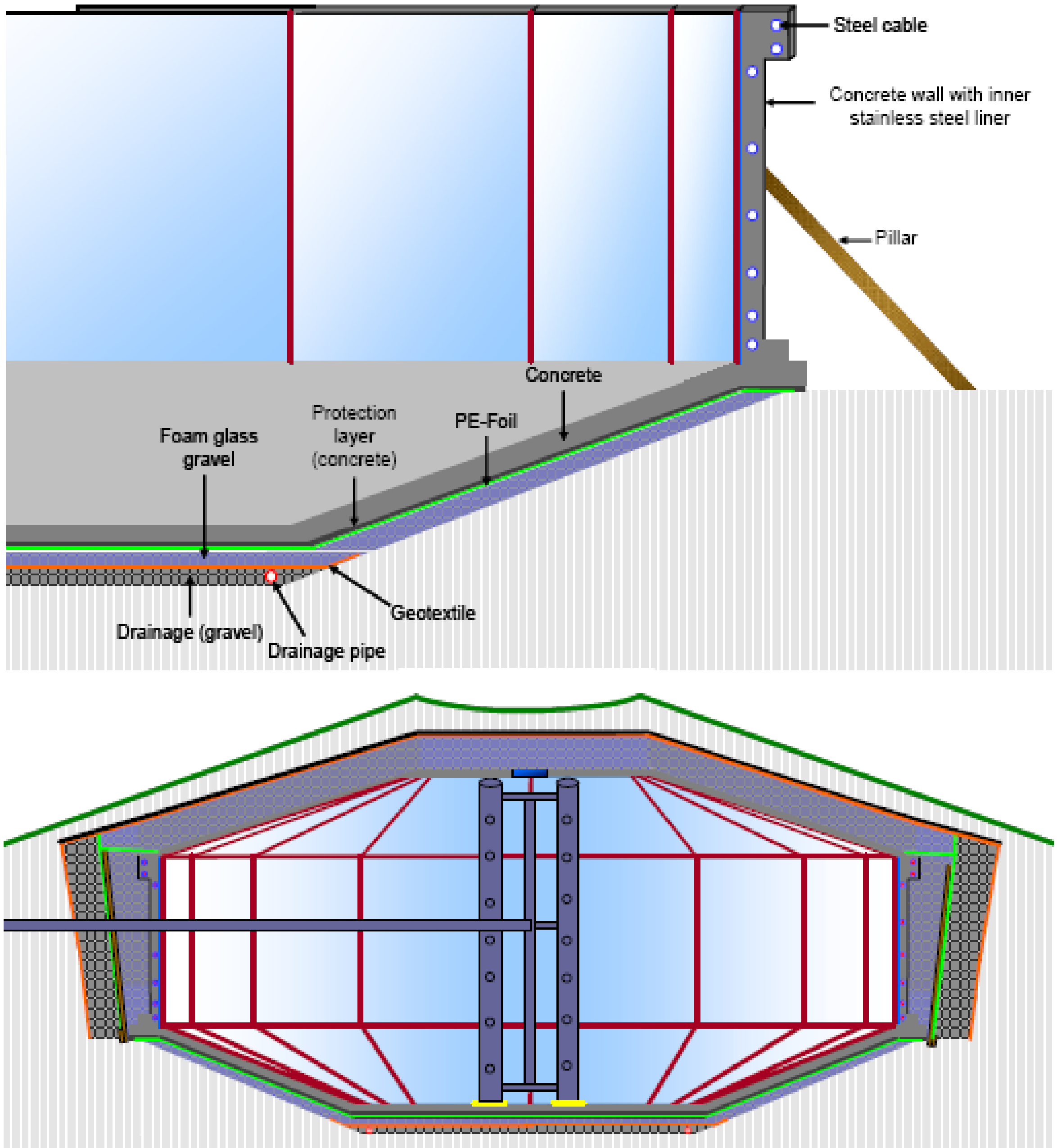

Figure 5. *Underground water tank constructed in Munich, Germany. The upper image shows the construction layout while the bottom image shows the center stratification device[Schmidt, 2006].*

Boreholes

Borehole technology, sometimes referred to as duct heat store, uses rock in the ground as the storage medium. The borehole is specifically the heat exchanger transferring the heat from the working fluid to the rock bed in the ground. Boreholes are deep holes drilled in the ground using mining technology typically ranging from 30 to 200 m deep. A u-tube (pipe that makes a 180 degree turn at the bottom) which carries the working fluid is placed in the hole and then the holes are filled with a highly conductive grout. The grout is usually made of sand, mortar, clay, and concrete. The heat from the working fluid is transferred to the grout and the grout conducts the heat directly into the surround rock bed.

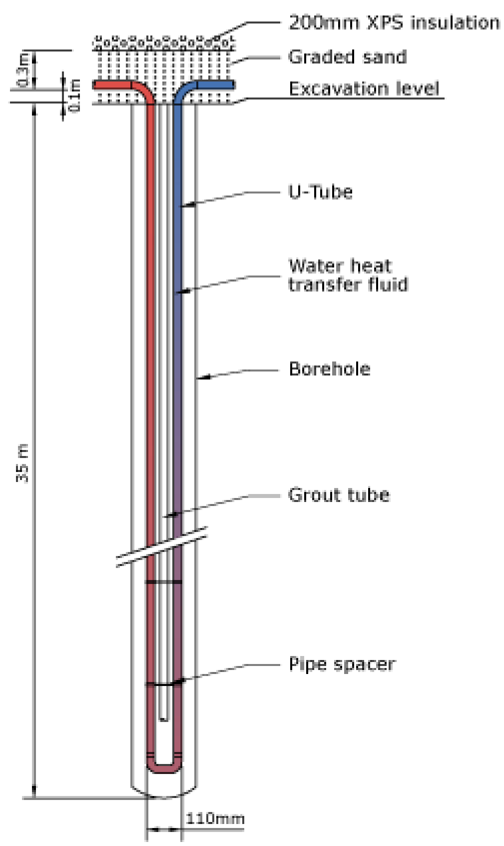

Figure 6. *A closed loop borehole used at Drake Landing [Drake Landing, 2009].*

In order to make a borehole seasonal thermal storage system work, several individual boreholes need to be drilled in a pattern throughout the ground volume to serve as the thermal storage bank. The holes can be connected in a serial configuration, in parallel, or in a combination of both. The warm working fluid from the collector enters the thermal storage bank at the center holes, as it leaves a center borehole it then travels outward to another borehole. This keeps the center of the storage bank the warmest and keeps the temperature gradient as the thermal storage bank expands outward low, minimizing conduction. Once the working fluid reaches the end of the thermal storage bank it is returned to the collectors. Often a heat exchanger exists between the working fluid of the collectors and the working fluid of the boreholes. This is so the working fluid from the boreholes can easily be reversed so that the cold working fluid from the outside of the storage bank can be brought back to the center to extract heat. Without a heat exchanger there has to be more boreholes drilled in a similar pattern so a separate network of u-tubes can extract the heat. Figure 4 shows three different patterns commonly used for a borehole thermal storage bank (square, circular, and expanding, respectively). Figure 5 shows movement of the warm working fluid and borehole pattern used at Drake Landing.

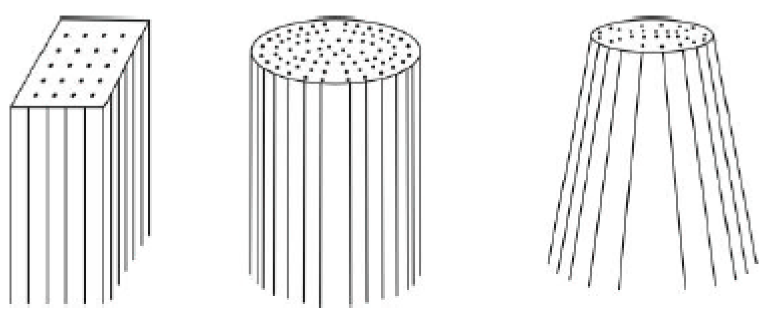

Figure 7. *Examples of different borehole drilling patterns commonly used [Nielsen,2006].*

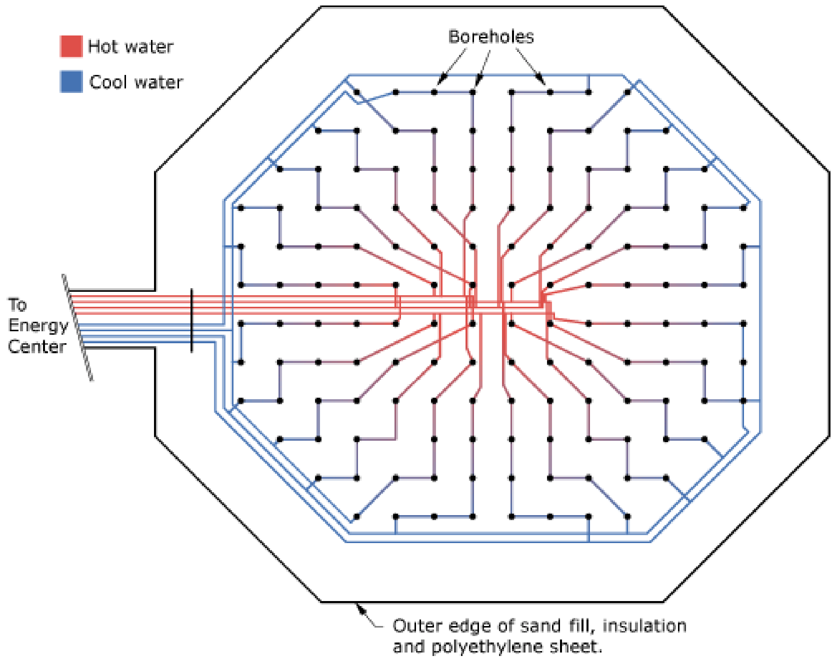

Figure 8. *Schematic of the warm working fluid starting at the center and moving outward of Drake Landing. There are 24 parallel sets of 6 boreholes in series (144 boreholes) beginning and ending at the Energy Center heat exchanger [Drake Landing].*

The surface of the borehole thermal storage bank must be insulated for maximum efficiency. Peak temperatures throughout the year in borehole storage banks range between 80-90^{o} C. Borehole technology will not work everywhere. The geologic conditions of the ground must be suitable for it to work. The two major factors in deciding if a borehole system will work is the specific heat of the ground, and the water flow. The higher the specific heat, the better suited the ground. Water flow through the storage bank will remove most of the heat stored. Almost all previous large scale projects have used the software programming called TRNSYS to model the performance of a borehole system.

ADVANTAGES/DISADVANTAGES OF TECHNOLOGY

The greatest advantage of this technology is undeniably the use of a clean renewable energy source for space heating. The major disadvantage of this technology is the high initial installation costs. Currently the only economically justifiable use of this technology is for large scale storage for multiple dwellings in climates that have both warm and cold seasons. District heating systems with seasonal thermal energy storage is, at maximum, twice as high as conventional heating costs [Schmidt, 2004]. However, due to the global political focus on reducing global warming, this technology may soon become a legislatively driven technology.

Borehole thermal storage and water tanks each have their advantages and disadvantages. Borehole storage only works well for large projects that need to store a lot of heat. The larger the borehole storage bank, typically the better efficiency it will have. However, it may take several of heating seasons for the storage bank to be filled. A major advantage for borehole storage is that during the summer months, the bank can be used as a heat sink for cooling a building which lowers air conditioning costs in the summer. The major disadvantage to borehole storage is geographic location. If the site of the project has poor soil conductivity and lots of water flow, then it will be impossible to install a successful borehole system. When the amount of desired thermal storage is large, then the borehole storage system is much more economical than an on-site construction of a large water tank. For smaller thermal storage a water tank may be more economic especially for a single home. Another advantage for a water tank is that it can be placed anywhere around the project site, above or below the ground. The major disadvantage for both types of storage is that the entire process of solar thermal collection and storage needs to be incorporated during the initial construction of the building as the technology is not well fit for retrofitting.

FUTURE EXPECTATIONS

Phase Change Materials

Phase change materials (PCM) exercise the use of latent heat storage. Latent heat is the heat acquired or lost during a phase change which is substantially more heat than in sensible storage. Energy densities for latent heat storage are greater than those for sensible heat storage (materials that don't change phases). A phase change from a solid to a liquid is the most desired because a change to and from a gas requires a lot of additional volume. Commercially available PCM have melting temperature ranges from -21 C (sodium chloride solution) to more than 200 C (salts and eutectic salt mixtures). Paraffin wax is also a popular PCM and is an easy to use product that can be made with melting points between -20 C and 120 C. The most studied PCM include Glauber's salt, calcium chloride hexahydrate, sodium thiosulfate pentahydrate sodium carbonate decahydrate, and disodium phosphate dodecahydrate [Kaygusuz, 1999]. Similar to a water tank, the PCM must be contained in a well insulated container. The working fluid must transfer its heat to the PCM container via a heat exchanger with some sort of stratification device for optimal performance. Figure 6 compares the thermal energy storage of a PCM to other types of sensible heat storage.

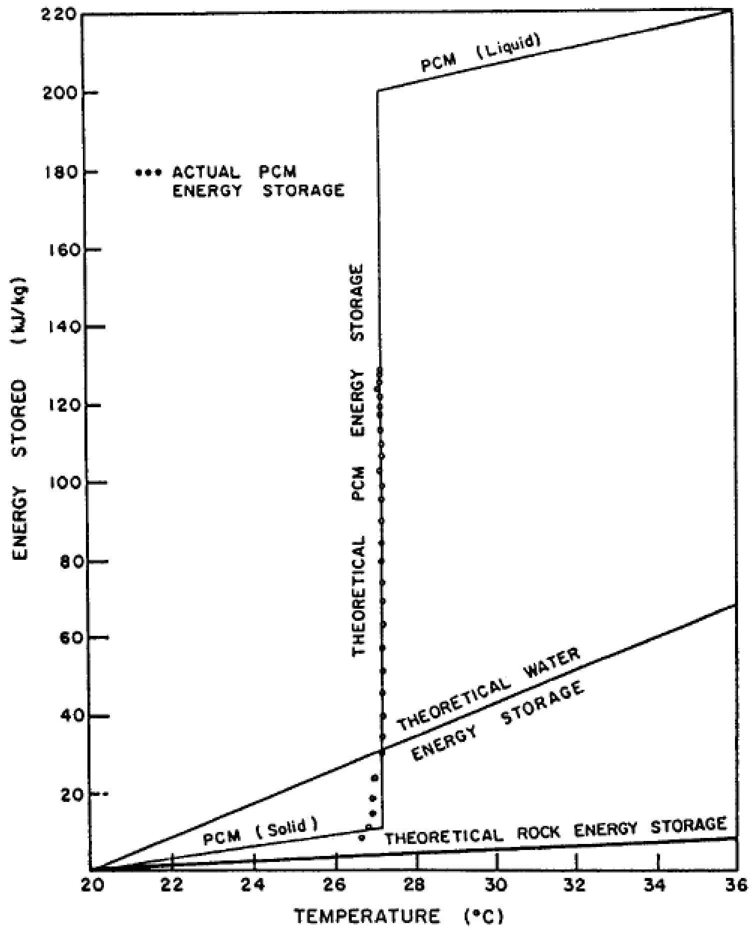

Figure 9. *Performance comparison of a PCM to sensible heat storage [Kaygusuz, 1999].*

Notice that the temperature remains constant during the phase change which is when most of the heat is stored. This means that the PCM must be made to the temperature specifications of the application. The difficulty using PCM for seasonal storage is that the temperature is tough to keep within the PCM specified temperature range. PCM are technically feasible as a storage medium but much more complicated. Another problem with PCM is that they tend to corrode and lose their designed phase change properties over time.

Thermochemical Storage

Thermochemical storage refers to a reversible chemical process, involving two media, which has the ability to gain and release heat during a chemical reaction. One concept uses a salt, such as sodium sulphide and water. The salt can be dried using solar thermal heat, which will cause it to accumulate thermal energy. This energy can then be recovered by adding water vapor to the salt. The concept of chemical reactions like this work “on paper” and in the lab, but are not yet feasible on a large scale. The salt in the reaction must be stored in a vacuumed environment which is nearly impossible to do on a large scale. Despite a number of proposals regarding chemical storage systems in chemical engineering research, there is yet to be a breakthrough in the field.

REFERENCES

E. Andersen and S. Furbo, "Theoretical Comparison of Solar Water/Space-Heating Combi Systems and Stratification Design Options," *Journal of Solar Energy Engineering*, Vol. 129, pp. 438-448, November 2007.

Y.H. Kuang, R.Z. Wang, L.Q. Yu, "Experimental Study on Solar Assisted Heat Pump System for Heat Supply," *Energy Conversion and Management*, Vol. 44, pp. 1089-1098, 2003.

A. Busso, A. Georgiev, and P. Roth, "Shallow Borehole Heat Exchanger: Response Test and Charging-Discharging Test with Solar Collectors," *Renewable Energy*, Vol. 31, pp. 971-985, 2006.

Kai Nielsen, "Thermal Energy Storage in Smart Energy-Efficient Buildings," A State-of-the-Art. Report. Smart Energy-Efficient Buildings Research Program at NTNU and SINTEF 2002-2006. Trondheim, January 2006.

Kamil Kaygusuz, "The Viability of Thermal Energy Storage," *Energy Sources*, Vol. 21, pp. 745-755, 1999.

M. Unsal and R. Yumrutas, "Analysis of Solar Aided Heat Pump Systems with Seasonal Thermal Energy Storage in Surface Tanks," *Energy*, Vol. 25, pp. 1231-1243, 2000.

Gerhard Faninger, "Thermal Energy Storage," *Proceedings of 5th International Summer School Solar Energy*, University of Klagenfurt, July 1998.

Bob Ramlow, "Warmed by the Sun in Wisconsin," *Renews*, Vol. 18, pp. 42-45, 2008.

T. Schmidt, D. Mangold, H. Muller-Steinhagen, "Central Solar Heating Plants with Seasonal Storage in Germany" *Solar Energy*, Vol. 76, pp. 165-174, 2004.

T. Schmidt, and D. Mangold, "New Steps in Seasonal Thermal Energy Storage in Germany," Steinbeis Research Insitute for Solar and Sustainable Thermal Energy Systems, 2006.

H.P. Garg, S.C. Mullick, and A.K. Bhargava, "Solar Thermal Energy Storage". 1985 by D. Reidel Publishing Company, Dordrecht, Holland. ISBN 90-277-1930-6

A. Brunger, J. Kokko, D. McClenahan, T. Onno, B. Sibbitt, J. Thornton, and B. Wong, "The Drake Landing Solar Community Project – Early Results" 2007

EIA. "US Carbon Dioxide Emissions from Energy and Industry." 2005. http://www.eia.doe.gov/oiaf/1605/ggrpt/carbon.html (March 10, 2009).

EIA. "Total Energy Consumption – All Tables." 2005. http://www.eia.doe.gov/emeu/recs/recs2005/c&e/summary/pdf/alltables1-15.pdf (March 10, 2009).

Drake Landing. "Drake Landing Solar Community." http://www.dlsc.ca/index.htm (March 10, 2009).