Aalto-yliopisto
Insinööritieteiden
korkeakoulu

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Thermal energy storage concepts and their feasibility

Diplomityö, joka on jätetty opinnäytteenä tarkastettavaksi
diplomi-insinöörin tutkintoa varten.

Espoossa 11.1.2016
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Työn nimi Lämmönvarastointimenetelmät ja niiden toteutettavuus

Laitos Rakenne- ja rakennustuotantotekniikka

Professuuri Kalliomekaniikka **Professuurikoodi** Rak-32

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Päivämäärä 11.1.2016 **Sivumäärä** 79 **Kieli** Englanti

Tiivistelmä

Tämä diplomityö on osa Suomen Akatemian projektia Solar Community Concept (SCC), jonka tarkoituksena on löytää tieteellisesti perusteltuja ratkaisuja suurimpiin haasteisiin ja ongelmakohtiin joita suomen ilmasto-olosuhteet asettavat aurinkolämpöä päälämmitysenergianlähteenä käyttävän aurinkokylän rakentamiselle.

Tämän diplomityön päätavoitteena on selvittää onko olemassa toteutuskelpoisia menetelmiä aurinkolämmön kausivarastointiin Suomen olosuhteissa? Ja jos, niin minkälainen kausivarasto sopii parhaiten SCC projektin tarpeisiin.

Seuraavia kausivarastointimenetelmiä tutkittiin kirjallisuustutkimuksen ja esimerkkitapausten avulla: pohjavesivarasto, porareikävarasto, luolavarasto, allasvarasto, säiliövarasto ja yhdistelmävarasto.

Suomen ilmasto, maaperä ja SCC projekti asetti varastointimenetelmille vaatimuksia ja rajoituksia, joita käytettiin arvioitaessa kausivarastointimenetelmiä. Eri menetelmien vaatima varastointitilavuus määritettiin käyttäen menetelmien varastointitehoja. Varastojen koon ollessa tiedossa käytettiin kirjallisuudesta saatuja hinta-arvioita kullekin menetelmälle. Ympäristön ja talouden asettamat rajoitukset otettiin huomioon valittaessa toteutuskelpoisinta menetelmää SCC projektille.

Arvioinnissa käytettyjen kriteerien puitteissa porareikävarasto osoittautui toteutuskelpoisimmaksi kausivarastointimenetelmäksi SCC projektille. Porareikävaraston etuja olivat yksinkertaisuus, pienikokoisen varaston toteutettavuus ja kustannustehokkuus.

Ehdotettu kausivarasto on tilavuudeltaan 62 000 m^3 ja siinä on 140 kappaletta 43 metriä syviä porareikiä. Hinta-arvio kausivarastolle vaihtelee välillä 0.3 M€ - 0.48 M€.

Avainsanat Lämpöenergia, Kausivarastointi, Aurinkolämpö, Aurinkokylä, Porareikävarasto, Pohjavesivarasto, Luolavarasto, Allasvarasto, Säiliövarasto, Yhdistelmävarasto

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Abstract of master's thesis

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Title of thesis Thermal energy storage concepts and their feasibility

Department Civil engineering

Professorship Rock mechanics **Code of professorship** Rak-32

Thesis supervisor Mikael Rinne

Thesis advisors Mateusz Janiszewski

Date 11.01.2016 **Number of pages** 79 **Language** English

Abstract

This Master's thesis is part of Finnish Academy project Solar Community Concept (SCC), which aims to find scientifically based methodologies and solutions for the major challenges and obstacles in the implementation of a solar community concept in the Finnish environment.

Main objective of this Master's thesis to find the most feasible method for seasonal storage of solar heat under Finnish conditions. Does Finnish ground and environmental conditions enable seasonal storing? And if, what kind of storage is best suited for the SCC project?

Following methods were studied with literature survey and case studies aquifer thermal energy storage (ATES), borehole thermal energy storage (BTES), cavern thermal energy storage (CTES), pit thermal energy storage (PTES), tank thermal energy storage (TTES) and combi storage which combines multiple methods.

Finnish environment, ground conditions and SCC project set some limitations and requirements for the storage. These limitations and requirements were taken into account in evaluation of different storage methods. Required storage volumes for each method were calculated. Required volume and cost estimates from literature were used when the most feasible method was chosen for SCC project.

Based on those criteria borehole thermal energy storage was chosen to be most suitable thermal energy storing method for SCC because of its simple, small scale feasible and cost effective features.

Suggested storage has storage volume of 62 000 m^3 with 140 boreholes. Boreholes are 43 meters deep and they are drilled into hexagonal. Cost estimate of the seasonal storage ranges between 0.3 M€ - 0.48 M€.

Keywords Thermal energy storage, Seasonal storage, Solar heat, Borehole storage, Aquifer storage, Cavern storage, Pit storage, Tank storage, Combi storage

Foreword

This Master's thesis is part of Finnish Academy project Tackling the Challenges of a Solar-Community Concept in High Latitudes, Work Package 2. Purpose of this thesis is to provide knowledge of different thermal energy storing methods for civil engineering research team working with Work Package 2.

I would like to thank thesis supervisor professor Mikael Rinne and thesis advisor Mateusz Janiszewski for their active guidance and commenting during the process of composing this master's thesis. Thank you Lauri Uotinen and Topias Sirén for your valuable ideas and comments. Thank you Juha and Joni for your support during our time together at Article Factory.

I would also like to give special thanks for my friends and family who have believed in me during all these years at Aalto University. Especially to you Niina, thanks for everything.

Espoo 11.1.2016

Mikko Honkonen

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T	[K]	temperature
U	[kJ]	internal energy
V	[m^3]	volume
c_p	[kJ/kg*K]	heat capacity
m	[kg]	mass
ρ	[kg m^{-3}]	density

Abbreviations

ATES	Aquifer thermal energy storage
BHE	Borehole heat exchanger
BTES	Borehole thermal energy storage
CTES	Cavern thermal energy storage
DHW	Domestic hot water
DLSC	Drake Landing Solar Community
EPS	Expanded polystyrene
EPDM	Ethylene propylene diene monomer
GWPTES	Gravel-water pit thermal energy storage
HDPE	High-density polyethylene
HTF	Heat transferring fluid
PCM	Phase change material
PE	Polyethylene
PHES	Pumped hydroelectric energy storage
PTES	Pit thermal energy storage
SCC	Solar Community Concept
SPH	Space heating
STTS	Short term thermal storage
TES	Thermal energy storage
UTES	Underground thermal energy storage
XPS	Extruded expanded polystyrene

1 Introduction

Increasing pressure to reduce greenhouse gas emissions from traditional energy sources has led to rising demand of energy produced with sustainable energy sources such as solar power. Problem with these popular renewable energy sources is that the times of supply and demand are not in line with each other. Most of the solar energy is radiated during few summer months and the biggest demand of heating energy is during from autumn to spring.

This issue with solar energy can be solved with thermal energy storage (TES). There are multiple possible solutions for this kind of storing ranging from simple sensible storages to more complex thermochemical storing methods. As the period of when the stored energy is used is long the energy amounts need to be stored are massive. As the stored amounts of energy are massive the unit cost for stored energy has to be low for the system to be feasible. These parameters set the limits for research in this master's thesis. The goal is to find a feasible method for storing great amounts of thermal energy for several months.

One most concrete and convenient example for usage of TES is a small neighborhood of houses that get great proportion of their heating energy from solar collectors. Solar collectors load the storage with thermal energy during summer months and that energy is extracted from the storage using heat exchangers during cold months. There are multiple solar communities in other European countries but no active villages in Finland.

This survey will be a part of project titled "Tackling the Challenges of a Solar-Community Concept (SCC) in High Latitudes". Main hypothesis of the research project can be formulated in the following way: Is it possible to build a solar community on a high-latitude location (like Finland) so that its energy management is largely based on renewable sources, it is economically feasible for all stakeholders and it is acceptable from the customer's as well as societal and environmental point-of-view.

Main objectives of this thesis is to find the most feasible method for seasonal storage of solar heat under Finnish conditions. Research question related to this objective is: Does Finnish ground and environmental conditions enable seasonal storing? And if, what kind of storage is the best suited for SCC project? Secondary objective is to recommend optimal design for chosen storage method. Research question related to this objective is: What design is most optimal based on technical and other criteria.

2 Thermal energy storage TES

2.1 Concept of TES

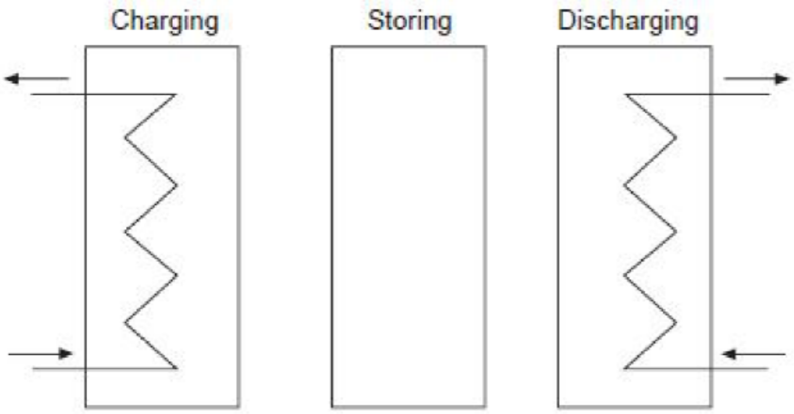


Figure 1: Storage cycle of TES system (Cabeza, et al., 2015)

Thermal energy storage (TES) is based on change in internal energy. Internal energy is increased when material is heated and lowered when material is cooled. This energy can be used later for heating or cooling. Thermal energy is stored in materials that are classified by one of three methods by which they store energy as heat: sensible heat, latent heat or thermochemical heat. Sensible heat means that all the energy stored in the material can be measured by the temperature difference between before the heating and after the heating as there is no phase change which would hide some of the stored energy. Figure 1 illustrates the basic concept of TES storage cycle. Desirable material for storage media is one that has large change in internal energy per unit volume and / or mass. This minimizes the space needed to store desired amount of energy. On the other hand economical aspect must be considered also. Media must have high internal energy change per unit cost to make storage economically feasible. Toxicity and corrosiveness of storage media must also be taken into account when choosing storage media. (Barnes, et al., 2011)

In a sensible heat storage the energy is stored to solid, liquid, or dual medium that has some combination of both medias. There is no change of phase or state e.g. from solid to liquid or from liquid to gas in the sensible heat storage. The internal energy change in sensible heat is depedent upon mass, specific heat, and temperature change:

$$\Delta U = mc_p(T_1 - T_2) \tag{1}$$

ΔU Represents the change in internal energy of the material in kilojoules, m represents the mass of the material in kilograms, c_p is the specific heat capacity and T_1 and T_2 are the initial and final temperatures of the material, respectively, in Kelvin. (Barnes, et al., 2011).

Latent heat storage is based on energy released or absorbed during a change of state or phase. Storage media in latent heat storages are phase change materials (PCM) that undergo significantly high change in internal energy during phase change. Molecular bonds of PCM are broken when heat is applied. This bonding energy give PCMs their exceptional heat capacity. Phase changing energy determines thermal storage capacity of PCM. Desirable PCM has high heat of transition, high density, appropriate transition temperature, low toxicity, and low time performance at low cost. (Barnes, et al., 2011)

PCMs are usually categorized into organic (paraffin waxes, fatty acids and, alkalines) or inorganic (salts). These listed PCMs have high volumetric energy densities and small tempereture swings which makes them good latent heat storage materials. Some primary advantages of latent heat storages are to store energy at reduced temperatures and reduced quantities and improved efficiencies (Pinel, et al., 2011). This makes the storage easier to fit in urban environment.

Thermochemical heat storage is based on energy stored as bond energy of a chemical compound. During thermochemical reaction atoms bonds are broken through a reversible chemical reaction and are catalyzed by an increase in temperature – which allows the energy to be stored. After thermochemical separation constituents are stored apart and recombined when needed. Recombination releases stored energy. Thermochemical storage allows to store energy with high density and long term low temperature storing. Disadvantages are that thermochemical materials are often expensive and they are often hazardous (Barnes, et al., 2011). Example of thermochemical reaction is methane steam reforming $CH_4 + H_2O = CO + 3H_2$ which has energy density of 6053 kJ kg^{-1}. (Hauer, 2013)

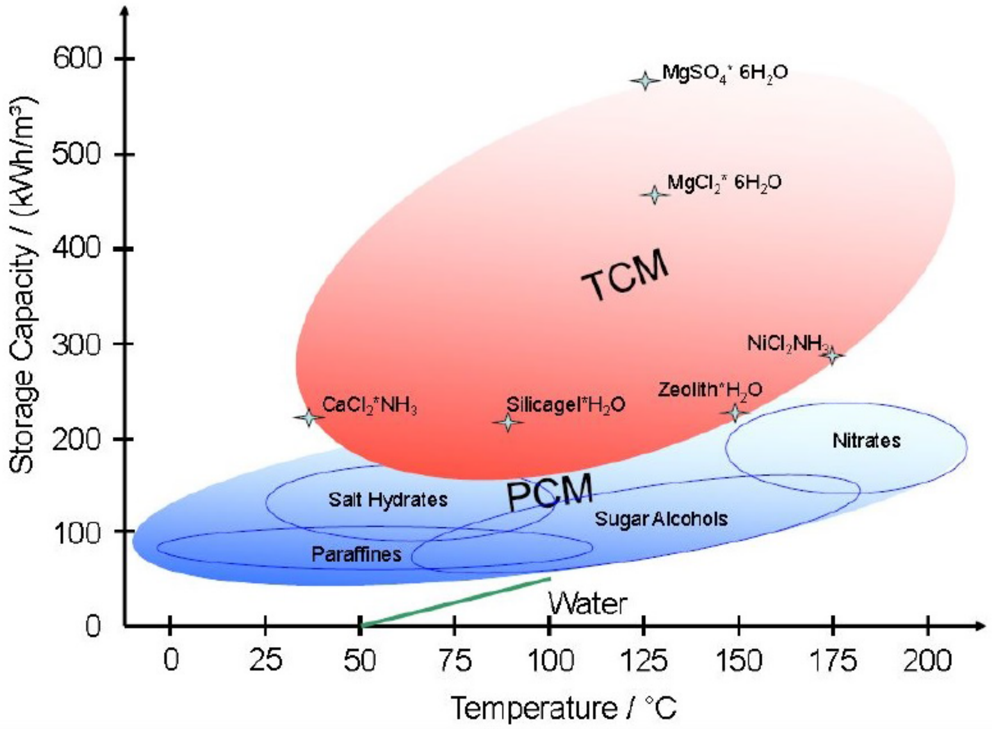


Figure 2: Storage capacity versus temperature (Hauer, 2013)

2.2 *What is TES suitable for*

Thermal energy storage is the most flexible method for energy storing when measured by size and storage times. It can be used for small scale short-term TES that is used by a single family home for storing cheap night time energy in a hot water tank to be used during the daytime as a source of heat for hot water. On the other hand it can be used as a seasonal storage method to provide energy for heating houses of a small village. (Nordell, 2000)

Seasonal storages are not limited only to heating as TES applications can be used to provide cold for space cooling with air conditioning. In short-term energy storages ice is generated during night and used during day time for cooling. Long-term solutions store winter cold, snow, or ice during winter months and use it during summer months to provide cold energy. (Alanen, et al., 2003)

2.2.1 Seasonal storage

Most of the annual solar energy is available during summer months. During these months energy demand for heating purposes is low. Problem caused by this mismatch is solved with seasonal storing of thermal energy. Storing duration with seasonal storing is several months and during those months stored energy is also consumed for heating purposes. Demanded energy amount that can fulfil this requirement is massive. (Nordell & Hellström, 2000)

Table 1: TES systems after (Hauer, 2013)

TES System	Capacity [kWh t^{-1}]	Power [MW]	Efficiency [%]	Storage period [h, d, m]	Cost [€ kWh^{-1}]
Sensible (hot water)	10-50	0.001-10	50-90	d/m	0.1-10
PCM (Phase change material)	50-150	0.001-1	75-90	h/m	10-50
Chemical reactions	120-250	0.01-1	75-100	h/d	8-100

Table 1 illustrates some rough estimates about sensible, latent and thermochemical reactions. It shows that latent and thermochemical TES methods have better storage capacity and efficiency, but the cost is significantly higher than in sensible methods. The cost of stored energy and demand for storing massive amounts of energy leads to that the latent (PCM) and methods using chemical reactions are not feasible for seasonal storing. By that conclusion the main focus of this Master's thesis is on sensible methods that are suitable for seasonal storage.

As the amount of stored energy is massive the storage media has to have great volume to be able to store the energy. Nordell and Hellström (2000) suggested that most favorable method to obtain this kind of volume of storage media, cost effectively, is to use soil or bedrock as storage media. Another great cheap option is to use water as storage media. Water has great thermal properties and it has cheap unit costs. (Pinel, et al., 2011)

2.3 TES technologies

There are several different technologies available for energy storing. While the main idea in sensible methods is the same, the technologies varies greatly. Each technology has its own advantages and requirements. Following chapters present different thermal energy storing methods that are capable to store energy seasonally.

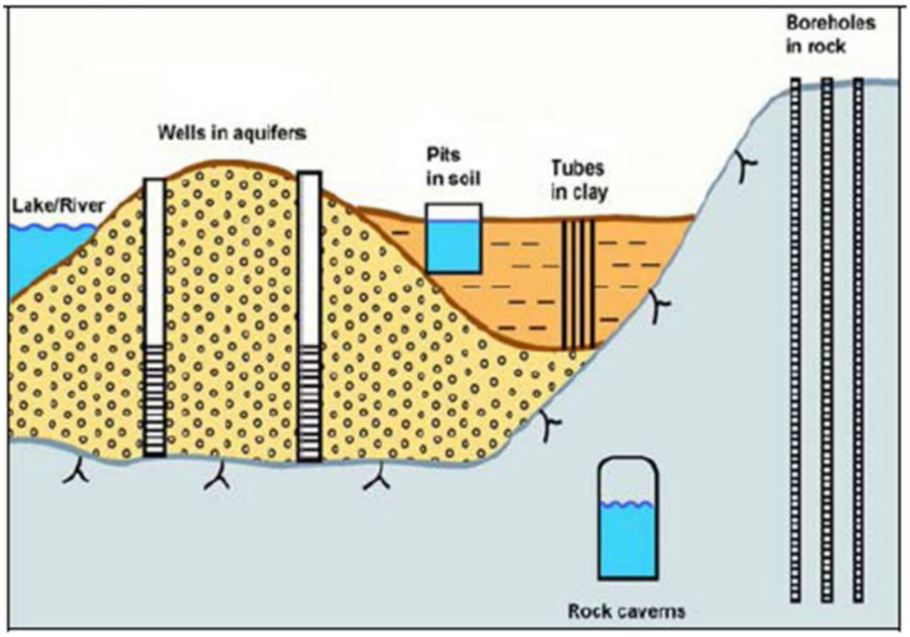


Figure 3: Outline of most common UTES applications (Nordell, et al., 2007)

UTES technologies developed since 1970s are (Novo, et al., 2010):

- Aquifer thermal energy storage (ATES)
- Borehole thermal energy storage (BTES)
- Cavern thermal energy storage (CTES)
- Pit storage (PTES)
- Tank thermal energy storage (TTES)

Table 2 has listing of thermal energy storages that are heated with solar energy. Solar fraction is a measurement that indicates how big portion of the heating energy demand is covered by solar energy.

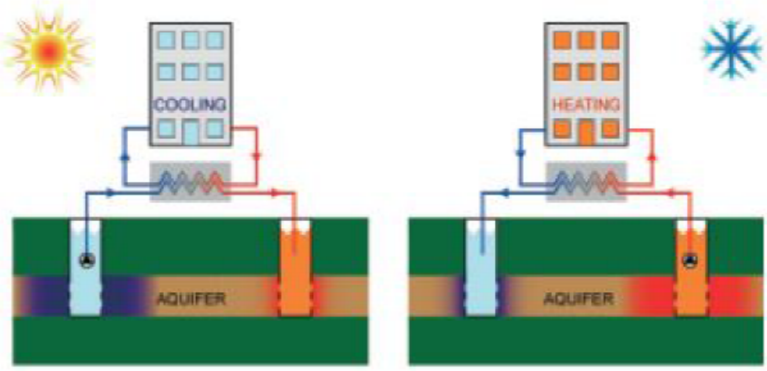
Table 2: List of TES projects after (Lozano, et al., 2014)

Name	Year built	Collector area [m^2]	Storage type	Storage volume [m^3]	Solar fraction	Investment [€]
Friedrichshafen	1996	4050	TTES	12000	0.47	3200000
München	2007	2900	TTES	5700	0.47	2900000
Mongolia	2012	5000	TTES	5000		
Hamburg	1996	3000	TTES	4500	0.49	2200000
Rise Fjernvarme	1998	3582	TTES	4000	0.8	697200
Hannover Kronsberg	2000	1350	TTES	2750	0.39	1200000
Aeroeskoebing	1998	4875	TTES	1400	0.2	1200000
Neuchatel	1997	1120	TTES	1000		
Tubberupvaenge	1991	1030	TTES	1000		1270000
Marstal Fjernvarme	1996	33000	PTES	75000	0.55	9440000
			PTES	10340		
			TTES	2000		
Ottupgaard	1995	565	PTES	1500		

Name	Year built	Collector area [m^2]	Storage type	Storage volume [m^3]	Solar fraction	Investment [€]
Chemnitz	2000	540	WGTES	8000	0.3	1400000
Augsburg	1998	2000	WGTES	6000		5100000
Eggenstein	2008	1600	WGTES	4500	0.37	1100000
Sonderborg Vollerup	2008	7681	WGTES	4000	0.2	
Steinfurt Borghorst	1999	510	WGTES	1500	0.34	500000
Neckarsulm Amorbach	1997	5670	BTES	63000	0.5	3500000
Anneberg	2002	2400	BTES	60000		
Crailheim	2003	7464	BTES	37500	0.5	4500000
Drake Landing	2007	2164	BTES	34000	0.98	2600000
Braedstrup	2011	18600	BTES	19000	0.3	1230000
			BTES	7500		
Attenkirchen	2002	800	BTES	9350	0.55	760000
Rostock Brinckmanshöhe	2000	980	ATES	20000	0.62	700000

2.4 Aquifer thermal energy storage ATES

Aquifer is an underground layer of water permeable rock, rock fractures or unconsolidated materials. These formations can be used as storage media for thermal energy. Energy is charged and discharged with pairing of hot and cold wells. There can be more than one pairing of wells in one aquifer. (Nordell, et al., 2007)



Summer: Cooling of office buildings / industrial processes

Winter: Heating of office buildings / industrial processes

Figure 4: Layout of aquifer storage. Impermeable ground layers are colored green in Figure 4 and the aquifer layer is colored light brown. (Hauer, 2013)

Figure 4 shows the basic idea behind the ATES system. When charging the aquifer with heat, water is pumped from the cold well to heat exchanger that is heating up the circulating water which is injected back to the aquifer trough hot well. The energy used for heating the water can be collected from solar collectors, industrial waste heat, or from ventilated air that is used for cooling the building. When discharging the heat from ATES system the direction of the water flow is simply reversed. (Schmidt, et al., 2000)

ATES system is suitable for seasonal energy storing and it can be simultaneously used for space cooling while charging the hot well. This simultaneous use is advantageous for charging the hot well, as the heat that is removed from a building is also injected to the hot well. (Nordell, et al., 2015)

Example of seasonal storage of thermal energy is when during summer the aquifer provides cool for ventilation to cool down the inside temperature of buildings and at the same time solar collectors are gathering heat for the heat exchanger that is heating up the water that is injected to the hot well. During winter this energy is used by reversing the circulation of water. Water that is pumped from the hot well is now cooled down by heat exchanger that is collecting the heat for the purpose of heating up the building. After losing the heat water is now injected back to the cold well so it can be used again during summer months.

When planning an ATES system important factor that has to be kept in mind is that the well pairings are not short circuiting with each other. Short circuiting in this case means that the water of cold well gets into contact with the water of hot well. This would even out the temperature difference and cause heat losses. This can be avoided with careful planning and modeling (Nordell, et al., 2015).

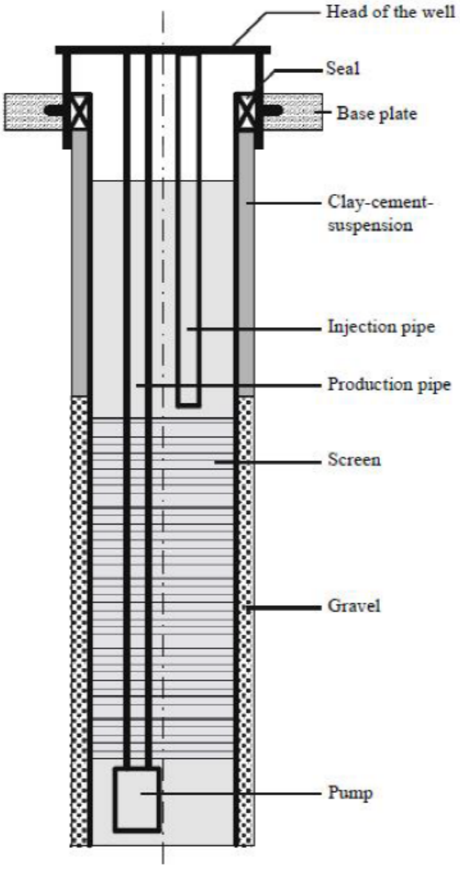


Figure 5: Cross-section of a well (Schmidt, et al., 2000)

The basic design of a well that is used in ATES system is illustrated in Figure 5. Because the charging and discharging the ATES is done by simply reversing the direction of the water flow every well has both injection pipe and pump. This minimizes the amount of drilling and helps to keep the system as simple as possible. Purpose of the screen is to keep the pump separated from the gravel to protect the pump from clogging.

2.4.1 Case: Aquifer thermal energy store in Rostock, Germany

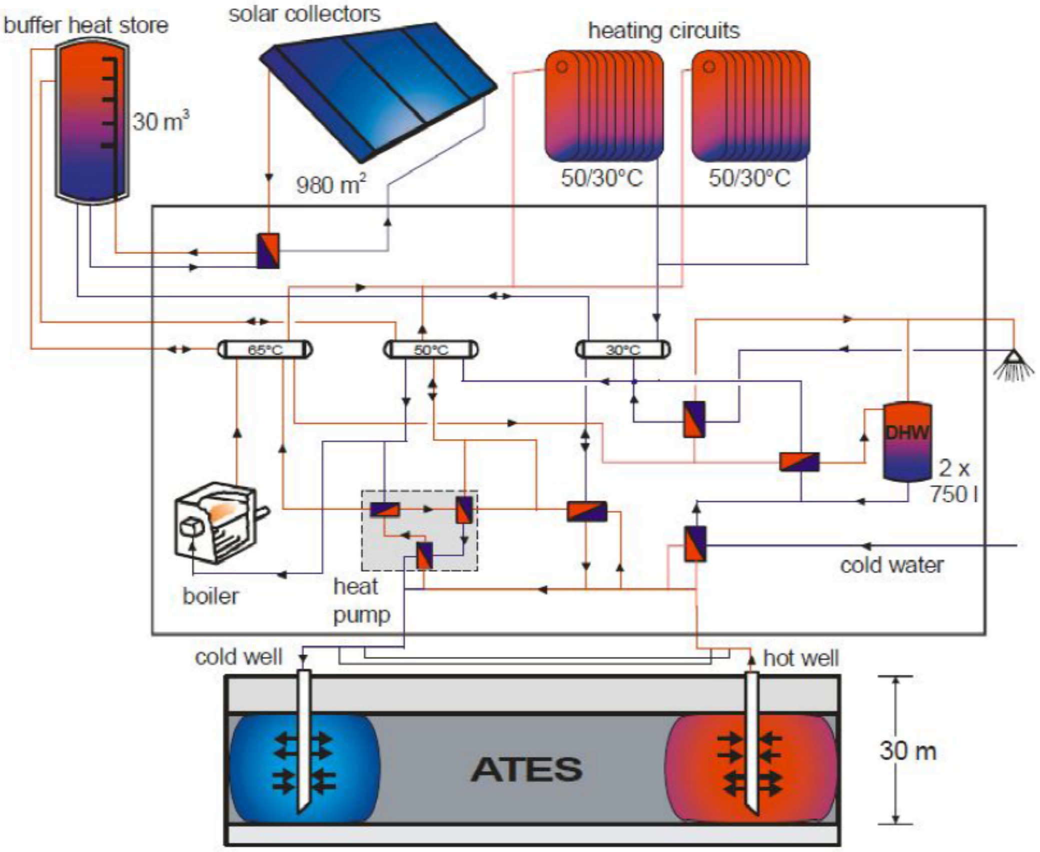


Figure 6: Scheme of the ATES system at Rostock (Schmidt & Müller-Steinhagen, 2004)

The first German central solar heating plant with ATES in Rostock went into operation during 2000. Heating energy is supplied to 108 apartments with combined heated area of 7000 m^2. Solar energy is provided by 980 m^2 of solar collectors mounted on the roofs of the apartments. ATES is operating with one pair of wells at depth of 15 – 30 meters with distance of 55 meters between the wells. (Schmidt & Müller-Steinhagen, 2004)

Figure 6 illustrates the heat supply system in Rostock. The heat is supplied on two different temperature levels 65 °C for domestic hot water (DHW) and 50 °C for space heating. The energy collected by solar collectors is stored into 30 m^3 water tank that acts as a buffer storage. Thermal energy is charged into the ATES from this short term thermal energy storage. DHW is provided from two 750 liter storage tanks. (Schmidt & Müller-Steinhagen, 2004)

Table 3: Design values of the Rostock central heating plant with seasonal storage after (Schmidt, et al., 2000)

No. Of apartments		108
living area	m^2	7000
heat demand:		
room heating	MWh a^{-1}	319
domestic hot water	MWh a^{-1}	144
distribution losses	MWh a^{-1}	34
total	MWh a^{-1}	497
max. Heat power	kW	250
collector area (absorber)	m^2	980
volume of ATES	m^3	20000
efficiency of ATES	%	63
thermal capacity of heat pump	kW	100
thermal capacity of gas condensing boiler	kW	250
design of floor heating system		45/30
collector heat generation	MWh a^{-1}	400
direct use	MWh a^{-1}	159
in ATES	MWh a^{-1}	234
from ATES	MWh a^{-1}	148
direct	MWh a^{-1}	2
via heat pump	MWh a^{-1}	146
geothermal energy from ATES	MWh a^{-1}	74
heat from gas condensing boiler	MWh a^{-1}	61
driving power of heat pump	MWh_{el} a^{-1}	55
solar fraction	%	62

The design values of the Rostock Central Heating Plant with Seasonal Storage (CSHPSS) is presented in Table 3**.** It shows that solar collectors can provide 307 MWh thermal energy per year when combining the numbers from directly used solar heat and thermal energy discharged from ATES system. Remaining energy demand is covered by conventional energy. When compared to a reference system with only a gas condensing boiler which has energy demand of 523 MWh per year the system saves 53% of the energy demand. (Schmidt, et al., 2000)

2.5 Borehole thermal energy storage BTES

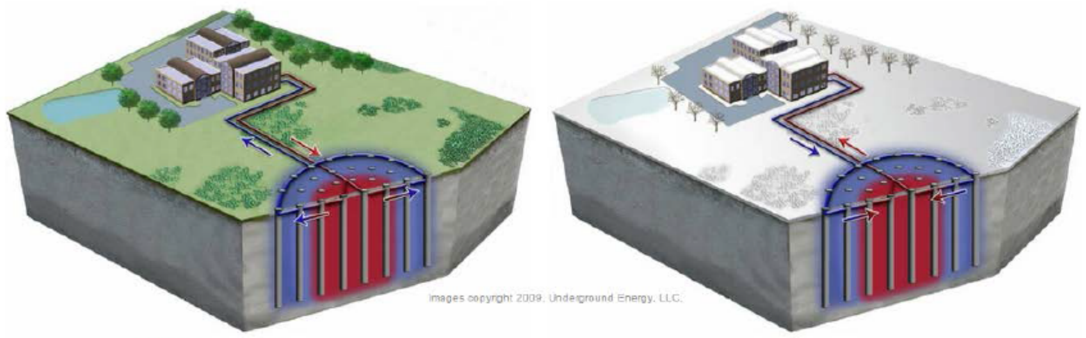
Borehole thermal energy storage (BTES) utilizes hard rock or soil as storage media by installing heat exchanger piping system into drilled borehole field. Flexibility is BTES systems advantage as the borehole field can be drilled in various ground types. Although BTES is more expensive than ATES due to multiple deep boreholes versus one or two pairings of boreholes in ATES systems, it is still most popular TES method due its flexibility. (Reuss, 2015)

Figure 7: Example of borehole field that has a football field on top of it (Wincott, 2011)

Figure 7 illustrates an example of borehole field that has been integrated into living environment by building a football field on top of it. A standard size soccer field with 140 m deep boreholes has the storage volume of 1 Mm^3. This shows that BTES system is feasible even in urban environments. (Wincott, 2011)

2.5.1 BTES technology

Basic idea of BTES system is to transfer heat into storage media, which is either soil or bedrock, with a piping system that acts as heat exchanger. Heat exchanger system is installed into drilled boreholes and it can be either an open system or a closed system. (Reuss, 2015)



BTES Summer Operation - Cooling

BTES Winter Operation - Heating

Figure 8: BTES loading and unloading seasonal storage. (Underground Energy, 2015)

Figure 8 illustrates how the BTES system works. During charging perioid the HTF that is heated up with heat extractors is pumped to the middle of the borehole field. The heat is now transferred to the rock mass via heat conduction. HTF travels trough multiple boreholes that are connected to each other by piping system. Boreholes are connected in parallel, in series, or in combination of both. By the time the HTF exits the borehole field at the edge its temperature has dropped and thermal energy is loaded into the rock mass. When this energy is needed the storage is discharged by reversing the flow direction of the HTF. The cold HTF is directed into outer edges of the borehole field and as the HTF flows trough borehole field it gets heated up by heat convection from the rock mass. This heat is then taken from the HTF by heat extractor and used as heating energy. (Sibbit & McCleanhan, 2014)

BTES systems can be divided into two main categories, open system and closed system. In the open HTF is in direct contact with borehole walls and in the closed system HTF circulates in closed pipe system without direct contact with borehole walls. (Nordell, 1994)

Closed systems

Closed systems are the most common application of BTES systems. Closed system consists of pipe system that circulates HTF from boreholes to heat exhanger. Piping can be done with one or more loops of U-pipe in one borehole. HTF is not in direct contact with borehole walls. To amplify the heat transfer into bedrock boreholes are filled either with special grouting or groundwater (Nordell, 1994)

Figure 9 illustrates a cross-section of a borehole with a single U-pipe. The heat transfer process of heat convection can be seen as the color coding for hot (red) changes to cold (blue) as the heat transfer fluid (HTF) circulates trough the loop in the borehole.

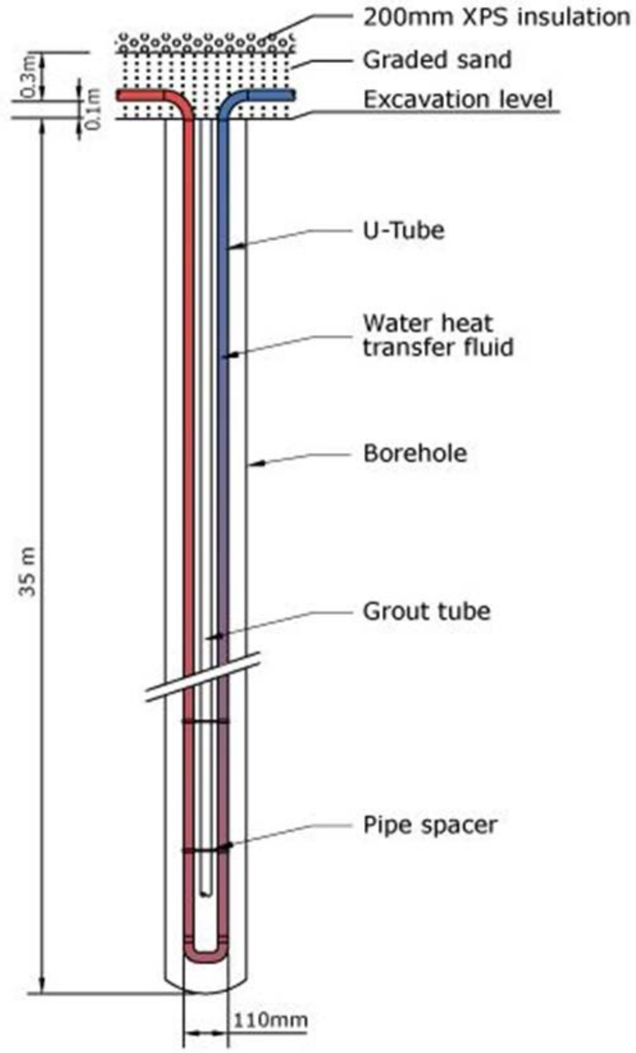


Figure 9: Cross-section of a single borehole with U-pipe (Drake Landing Solar Community, 2015)

Open systems

Open systems are usually built by installing a pipe in centre of the borehole. Water is pumped into bottom of the borehole through this pipe. After leaving the pipe water is flowing upward with direct contact to borehole walls. Depending on loading cycle water is now either loading or extracting heat from BTES. This direct contact with borehole walls is main advantage of open systems. The heat is conducting more efficiently between

HTF and storage media. One disadvantage is that direct contact with borehole walls may cause problems with water chemistry when hot water and rock react. (Nordell, 1994)

Combined system

Combined system is designed to have advantages from both open and closed systems. Boreholes are covered with thin watertight rubber coating. This thin coating minimizes losses in the heat conductivity while keeping the system closed so anti-freeze and other chemical can be used. (Nordell, 1994)

Borehole field

Hexagonal and rectangle shapes are in favor when planning the borehole field. Most compact solution for storage is attained when diameter of borehole field and depth of boreholes are roughly equal. Distance between boreholes varies between 2 – 5 meters. The distance between boreholes depends on thermal conductivity of rock mass. If thermal conductivity is low boreholes are located closer to each other to maximize heat transfer into rock mass. (Reuss, 2015)

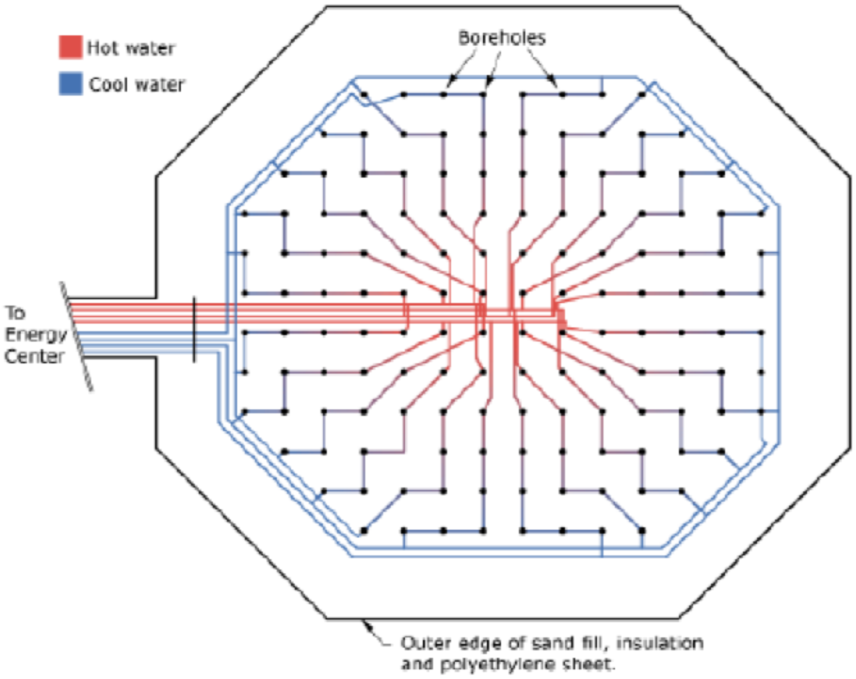


Figure 10: Hexagonal configuration of borehole field (Drake Landing Solar Community (2015))

Figure 10 illustrates the hexagonal configuration of borehole field at Drake Landing Solar Community. Each of 24 strings with 6 boreholes in each begins from the middle of the borehole field and expands to outer edges of the borehole field.

2.5.2 Ground parameters needed when planning BTES system

When planning a BTES system thermal properties of the ground are the most important factors that must be considered. Heat capacity does not fluctuate that much between different rock types and usually it lies around 0.06 kWh m^{-3} K^{-1}. Thermal conductivity has much greater role when selecting optimal site for BTES as it fluctuates considerably between different rock types. (Nordell, 1994)

The volume needed for storage can be calculated with equation 2.

$$V = \frac{E_+}{\Delta T} * C \tag{2}$$

Where V = storage volume [m^3]
E+ = stored energy [kWh]
C = volumetric heat capacity [kWh m^{-3} K^{-1}]
ΔT = temperature difference (max-min) of the volume [K] (Nordell, 1994)

Table 4: Thermal properties of storage media (Nordell, 1994)

Type of medium	Density [kg m^{-3}]	Thermal Conductivity [W m^{-1} K^{-1}]	Heat Capacity [kJ kg^{-1} K^{-1}]	Volumetric Heat Capacity [kWh m^{-3} K^{-1}]
Granite	2700	2.9 – 4.2	830	0.62
Pegmatite	2700	2.9 – 4.2	860	0.62
Syenite	2650	2.2 – 3.3	850	0.65
Diorite	2800	2.2 - 3.3	850	0.66
Gabbro	3000	2.2 – 3.3	860	0.72
Diabase	3000	2.2 – 3.3	860	0.72
Sandstone	2700	3.0 – 5.0	730	0.55
Clayshale	2800	1.7 – 3.5	850	0.66
Limestone	2700	1.7 – 3.0	840	0.63
Quarzite	2650	5.0 – 7.0	790	0.58
Gneiss	2700	2.5 – 4.7	830	0.62
Leptite	2700	2.5 – 4.5	830	0.62
Marble	2700	2.5 – 3.5	770	0.58
Water	1000	0.62	4180	1.18

Table 4 illustrates properties of different rock types. Gabbro and Diabase has the highest volumetric heat capacity which is desirable and sandstone has the lowest volumetric heat capacity. Table 4 also shows that water is great storage media for thermal energy storage that has operational temperature boundaries set by waters freezing point and boiling point.

One major challenge with BTES systems is that they can only be insulated cost effectively on the ground level. Stored heat escapes from the storage trough sides of the storage and even with insulation top of the storage it is the side which leaks away most of the energy compared to other sides. The heat escapes because of the temperature difference between the storage and the surroundings. In early years escaping thermal energy heats up the surrounding bedrock and the heat losses to surroundings are more severe than after few years. (Reuss, 2015)

”The surface-to-volume ratio should reach an optimum (maximum volume / minimum surface), as the storage capacity is proportional to the volume and the heat losses are proportional to the surface. (Reuss, 2015)” As heat losses are caused by conduction to surroundings trough surfaces of BTES optimization of volume-to-surface ratio is the key to minimize heat losses. A storage with a small volume is suffering from relatively bigger heat losses than a similarly shaped storage with bigger volume. For example storage that is shaped as a cube has six sides which act as surface. The area (A) of these surfaces is calculated by Equation 3

$$A = 6 * x^2 \tag{3}$$

Where the x is the length of a side of the cube.

And the volume (V) is calculated by Equation 4

$$V = x^3 \tag{4}$$

Where the x is the length of a side of the cube.

By comparing these two equations it is clear that volume-to-surface ratio is growing as the storage gets bigger. This leads to that heat losses gets relatively smaller as the storage volume grows. According to Nordell (2007) the first high temperature BTES system built in Sweden had storage volume of 120 000 m3 and the heat losses were 40 % of the stored energy. This number could be reduced to levels of 10 – 15 % with a larger storage that has volume of few hundred thousand cubic meters.

2.5.3 Hydraulic fracturing

Hydraulic fracturing is method for creating man made fractures into bedrock. These fractures are caused by high pressure that is applied to bedrock via boreholes (Ramstad, 2004). At shallow depths horizontal stress in the bedrock is much greater than vertical stress that is mostly caused by the mass of the bedrock above. This causes vertical stress to be least principal stress and fractures will propagate horizontally. (Hellström & Larson, 2001)

When fracturing hydraulically a packer is placed into the borehole. After the packer is placed correctly it is inflated so that it will make a water tight connection between borehole walls acting as a plug. These packers can either be single or dual packers depending on the placement of the fractures. Single packer can be used when fractures are made at the bottom of the borehole and dual packer is used when fracture zone is wanted somewhere other than the bottom. When the packer is inflated pressure that will fracture the bedrock is caused by slowly pumping water into the space between packers or the packer and bottom of the borehole. (Ramstad, 2004)

Main reason for using hydraulic fracturing when creating a seasonal storage is that it lowers the amount of needed boreholes and this leads to direct cost savings that can reduce the size of economically feasible borehole thermal energy storage. (Hellström & Larson, 2001)

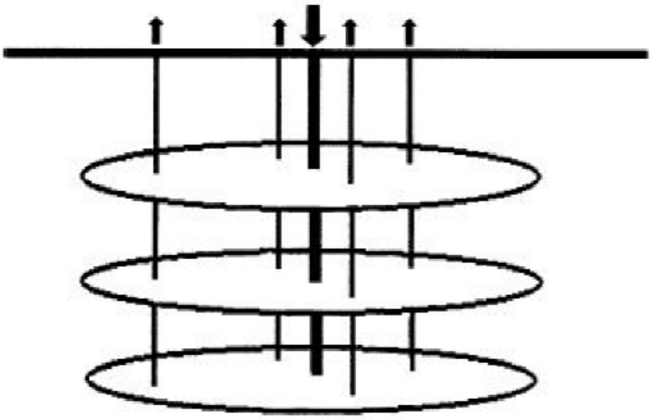


Figure 11: HYDROCK concept (Hellström & Larson, 2001)

Figure 11 illustrates a basic concept of a hydraulic fracturing method called HYDROCK that was invented in Sweden during 1983. An injection well is placed into middle of extraction wells that are located evenly on a constant radius from the injection well. Number of horizontal fracture zones are made by hydraulic fracturing. These fractures connect the injection well and extraction wells into each other. Thermal energy is injected to the storage by pumping hot water into the injection well. The pumped hot water is extracted from extraction wells. The heat is stored to the rock mass by heat convection when the water travels from injection well to the extraction well. (Hellström & Larson, 2001)

Hellström & Larson (2001) made a comparison between storage with HYDROCK concept and two traditional BTES systems. The HYDROCK concept had circular horizontal crack planes with radius of 25 m. The uppermost crack plane was located 20 m from surface and the lowest crack plane was located at 68 m so the storage volume is roughly 100 000 m^3. Other BTES had 61 boreholes at 125 m for the 4 m spacing between boreholes and the other BTES had 108 boreholes when spacing was 3 m. Simulations were done by Hellström's (1989) duct ground heat storage model (DST).

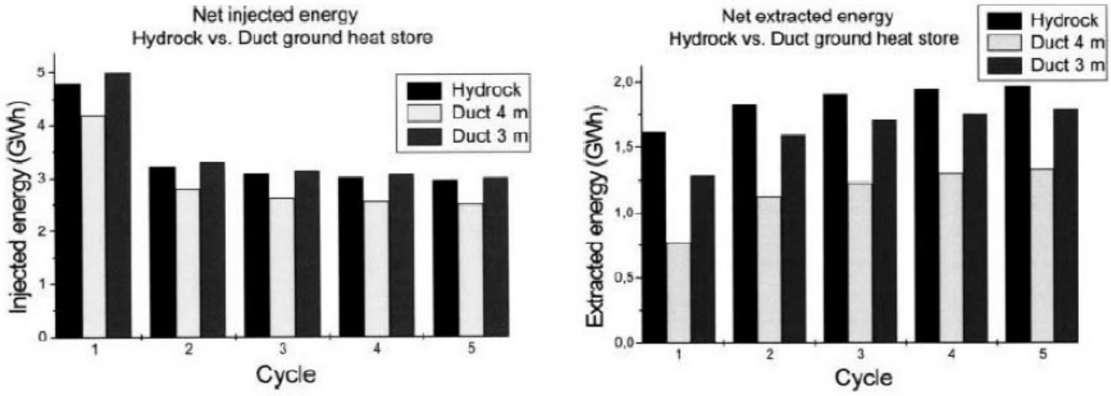


Figure 12: Comparison of HYDROCK and BTES. Picture modified from (Hellström & Larson, 2001)

Figure 12 illustrates that the injected energy amounts were about the same between different methods but extracted energy from the HYDROCK method was 10-20% more than from BTES methods. (Hellström & Larson, 2001)

2.5.4 CASE: Drake Landing Solar Community DLSC

Drake Landing Solar Community located at town of Okotoks, Alberta, Canada is a community of 52 houses that are using solar energy as their main source of heating energy. Building phase of the village was completed at August 2007. Each house has a garage that has solar collectors mounted on its roof. Combined surface-area of those solar collectors is 2313 m^2. Those solar collectors are connected to a energy center with insulated pipeline network. Energy center is the heart of DLSC as it collects solar energy into short term thermal storages and distributes heat to houses and BTES system. (McClenahan, et al., 2006)

Borehole field of DLSC contains 144 boreholes that are 35 meters deep each. The field is constructed from 24 strings of 6 boreholes. The borehole field covers 35 meters in diameter. The BTES system has volume of 34000 m^3. Each string begins from central area of the borehole field and extends towards the edge of the borehole field. Heat transferring fluid is directed so that heated fluid always enter the field at the centre. After few years of loading cycles the borehole field will reach its maximum temperature of 80 °C (McClenahan, et al., 2006). According to Leidos Canada (2014) maximum temperature of BTES system that was reported during years 2012 – 2013 was 74.7 °C.

Houses are connected to a district heating loop that is controlled from energy center. Energy center has two insulated water tanks that work as short term thermal storage. Volume of these tanks is 120 m^3 each. Those tanks act as a buffer when heating the BTES system or when heat is extracted from BTES. This buffer allows the BTES to be charged even when there is temporary lack of solar energy. Buffer storages can also provide heating energy (McClenahan, et al., 2006)

System control at DLSC

The mixture of glycol and water is heated up by the solar collectors. When the heat transfer fluid (HTF) in the collector loop is hot enough the heat is transferred into the Short term thermal storage (STTS) tanks with a plate heat exchanger. When the HTF is cool enough it is sent back to circulate the collector loop. (Sibbitt, et al., 2011)

District loop is connected to the STTS that is providing the thermal energy for heating. If there is an insufficient amount of heat stored in the STTS heat is transferred from BTES system to balance this shortage. In emergency situation where the amount of heat transferred from the BTES is not enough natural gas fired boilers can be used to meet this energy deficit. (Sibbitt, et al., 2011)

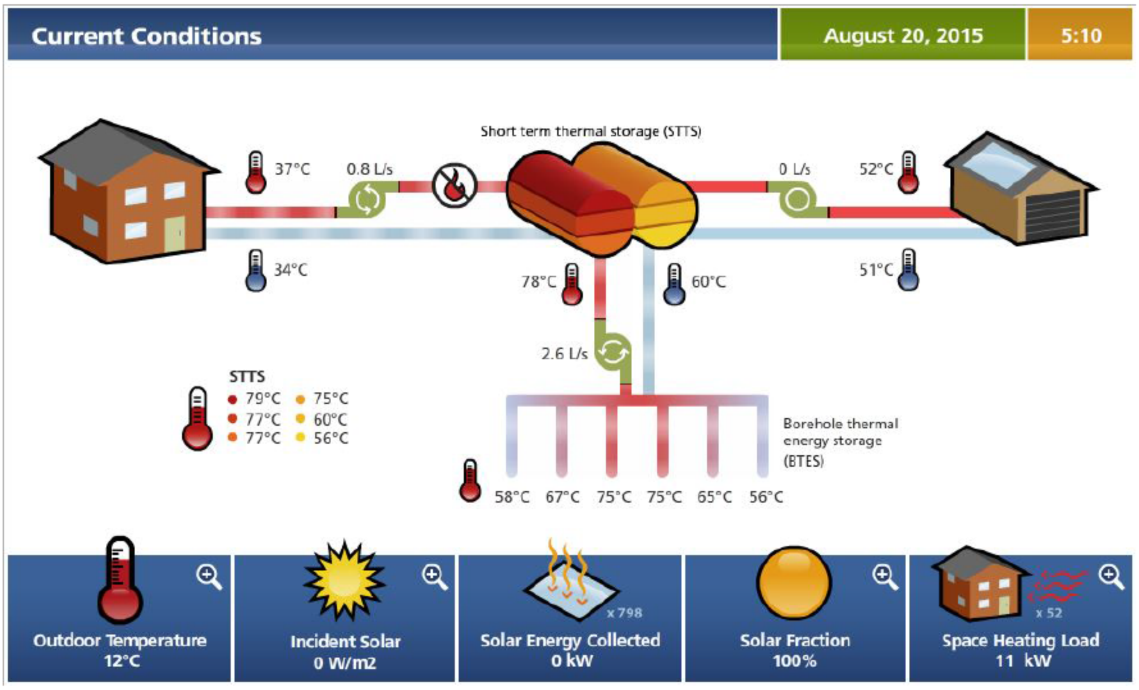


Figure 13: Drake landing system conditions (Drake Landing Solar Community, 2015)

Figure 13 illustrates the actual system conditions of DLSC on August 20, 2015.

It is important to get the HTF cooled down to levels that were used at the planning stage. Mismatch with these values reduces the efficiency of the solar collector loop and this affects the whole process chain negatively. (Sibbitt, et al., 2011)

Performance of DLSC solar collectors and thermalenergy storages

Annual report, by Leidos Canada (2014), of system performance from Drake Landing Solar Community web page shows that the system is really achieving the goal of providing over 90% of the heating energy with solar energy as the system has reached solar fraction of 98%.

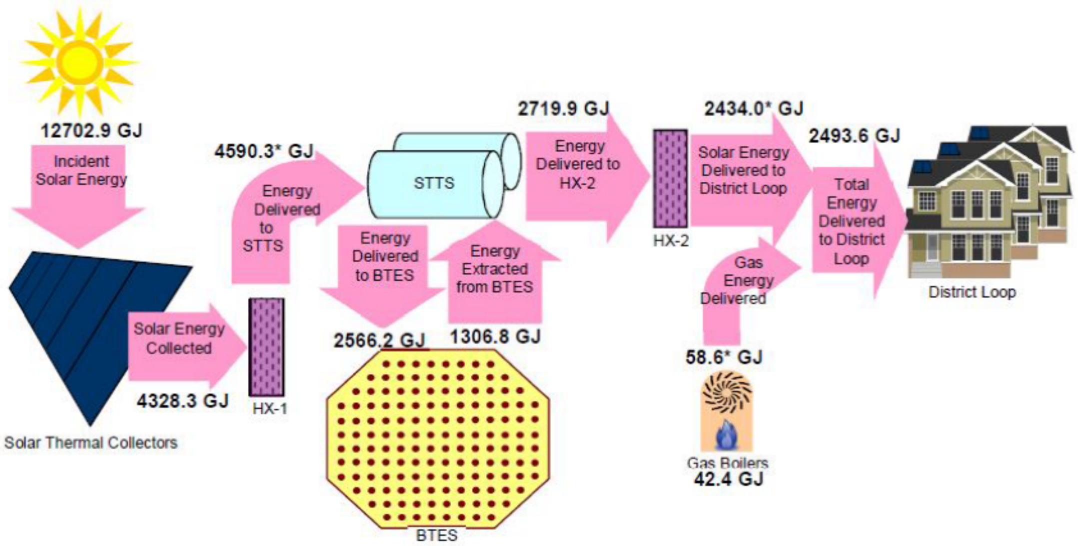


Figure 14: System energy flow diagram of DLSC. (Leidos Canada, 2014)

Figure 14 shows the annual energy flows from sun and gas boilers that is the total energy delivered to district loop. As the diagram shows most of the energy is coming from solar collectors. High heat losses of the BTES system can also be seen from the Figure 14 as 2566.2 GJ enters the BTES system but only 1306.8 GJ is extracted.

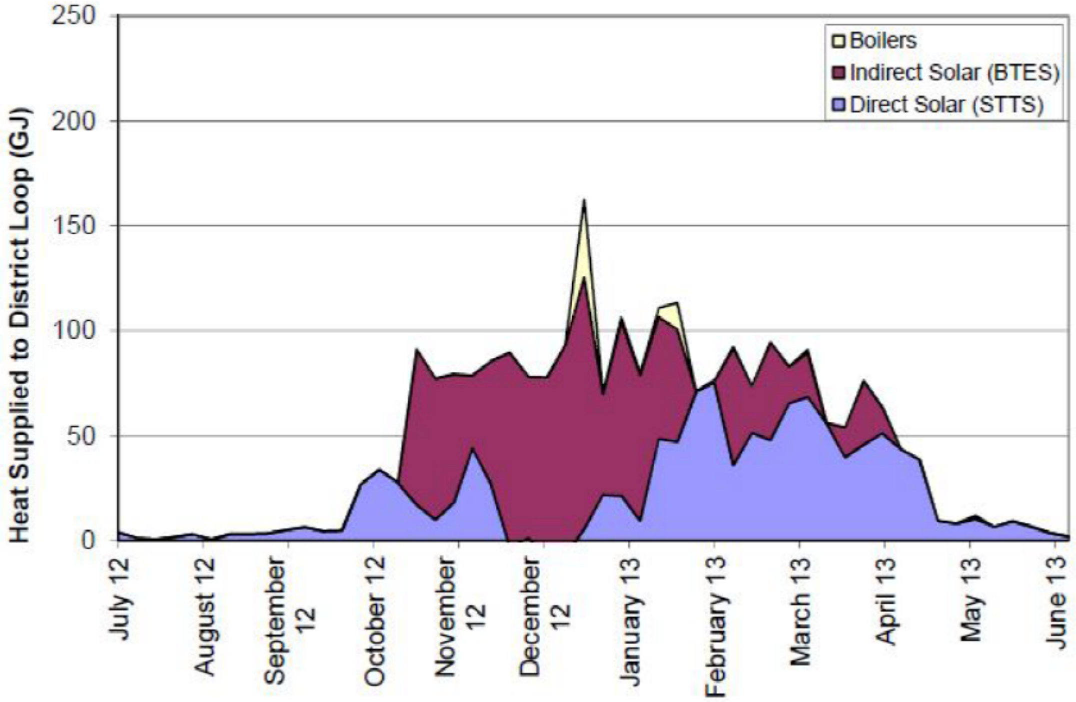


Figure 15: Weekly energy distribution by source (Leidos Canada, 2014)

Figure 15 illustrates the weekly heating demand of DLSC between July 2012 and June 2013. During May to September there is really low demand of heating energy and that can be provided directly via solar collectors and STTS. At the beginning of September

2012 energy demand rises significantly but it still can be managed with direct solar. At the end of October climate changes in a way that reduces amount of direct solar energy and it also gets colder as heat demand rises sharply. Energy storage is now providing most of the heat. At end of the December demand of heating is so high that boilers need to provide some of the heat for two weeks. Boilers are also used during end of January for two weeks. There is a brief sunny period during February when direct solar meets the whole demand of heating energy. By the end of April the heating energy demand has permanently dropped to a level where direct solar covers the whole demand. Figure 17 illustrates how the storage temperatures increases from April to end of October as it is charged and the temperature of the storage declines during winter months when the energy is discharged.

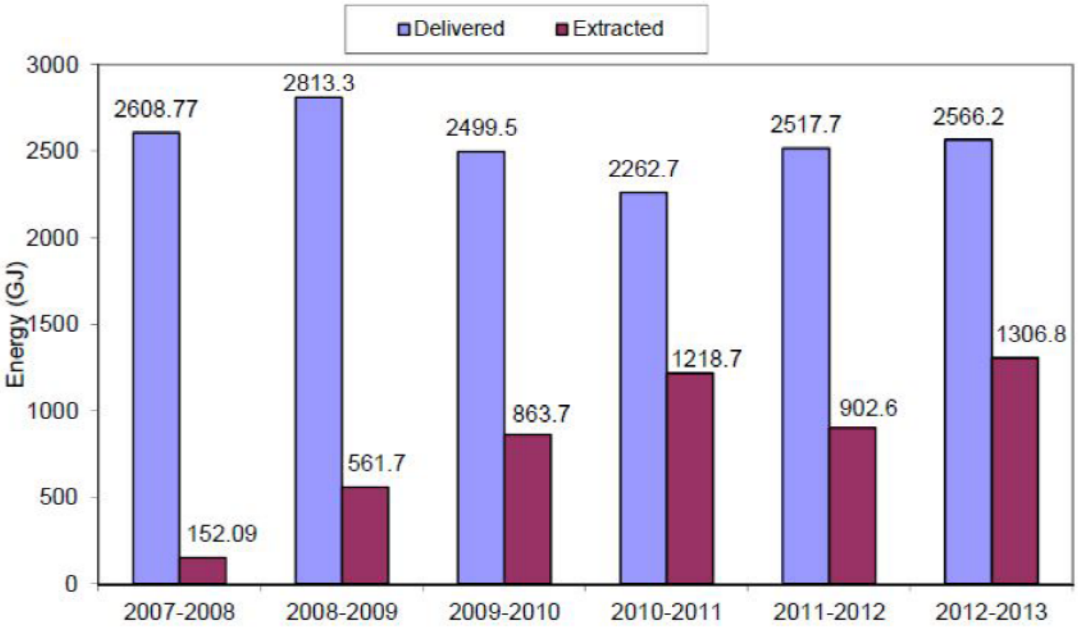


Figure 16: Annual BTES energy flow (Leidos Canada, 2014)

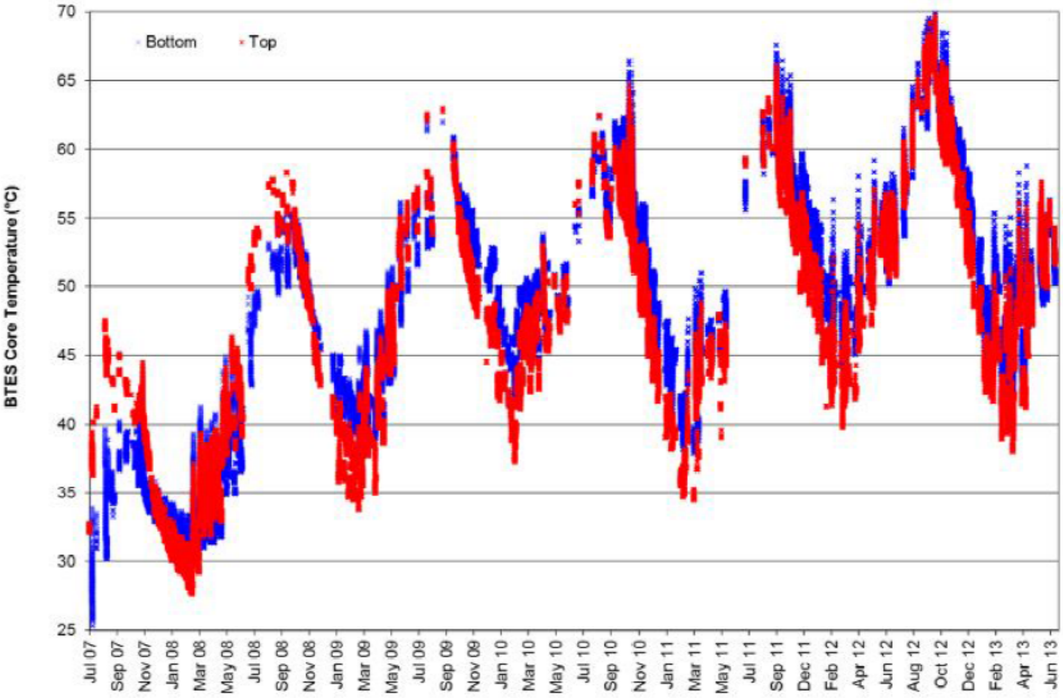


Figure 17: Core temperatures of DLSC BTES system. Red dots illustrate readings from a sensor that was placed at the top of the borehole and blue dots are readings from a sensor at the bottom of the borehole. (Leidos Canada, 2014)

Figure 16 illustrates that most of the energy that is charged during early years of energy storing is lost as heat losses as the energy goes into heating up the surrounding soil. This happens because the soil inside and around the storage has to be heated up. Figure 17 illustrates the core temperature of the BTES system as function of the time. Every year the maximum core temperature has increased although the amount of energy that is charged to the storage has remained somewhat constant.

2.6 Cavern Thermal Energy Storage CTES

Cavern storages use underground space as water reservoir. The water stored in cavern is used as storage media for thermal energy. Building a new cavern is a possibility, but initial expenses are high and large storage volumes are required before excavating the new cavern becomes economically feasible. Finding an existing cavern can decrease investment costs greatly. Old abandoned mines and oil storages can be modified to act as water reservoir for CTES system. Only restriction is that the groundwater leakage to cavern must be minimized as it leads to heat losses. (Lee, 2013)

Caverns are located so deep that they are not affected by seasonal fluctuations in air temperatures. Heat losses occur only by heat convection trough surrounding rock masses. Storage walls are not insulated and the water is in direct contact with cavern walls. This leads to that the heat losses are substantial during early years because of the substantial temperature difference between surrounding rock and water in the storage. After year or two surrounding rock is heated to storing temperatures and the storage has less than 10 % losses due heat convection. (Lee, 2013)

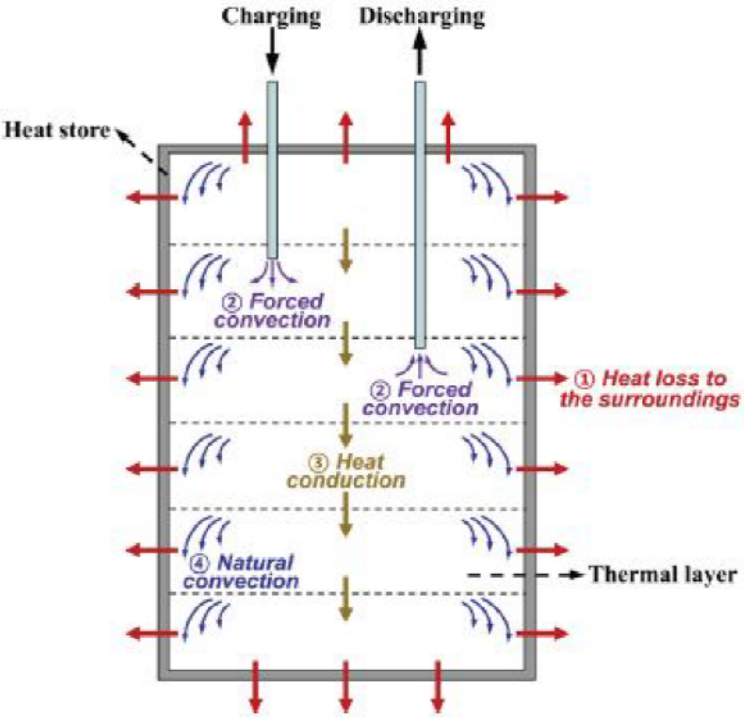


Figure 18: Factors that affect thermal stratification (Park, et al., 2014)

Usually the volume of the cavern is massive and therefore the caverns are capable of storing great amounts of thermal energy. When storing thermal energy into water thermal stratification is important factor as it helps to minimize heat losses when charging the storage. Thermal stratification is caused by difference in water density in different temperatures. Hot water being lighter than cold water the water forms layers of different temperatures. Figure 18 illustrates factors that are affecting thermal stratification. Being aware of this fact water can be injected into correct layer to avoid mixing different water temperatures. (Park, et al., 2014)

Water stratification can be improved by changing the aspect ratio of the storage. Aspect ratio is the ratio between height of the cavern and width of the cavern. The higher the aspect ratio, the better the thermal stratification is but this causes problems with mechanical stability of the cavern. Storage must be planned so that safety is not compromised and thermal stratification is optimal. This may lead to that the storage is not shaped as one big cylinder with high aspect ratio, but as few smaller cylinders with high aspect ratio or as shape of toroid. For a toroid shape storage aspect ratio of 3.5 is optimal as the thermal stratification is not improving remarkably beyond that aspect ratio. (Park, et al., 2014)

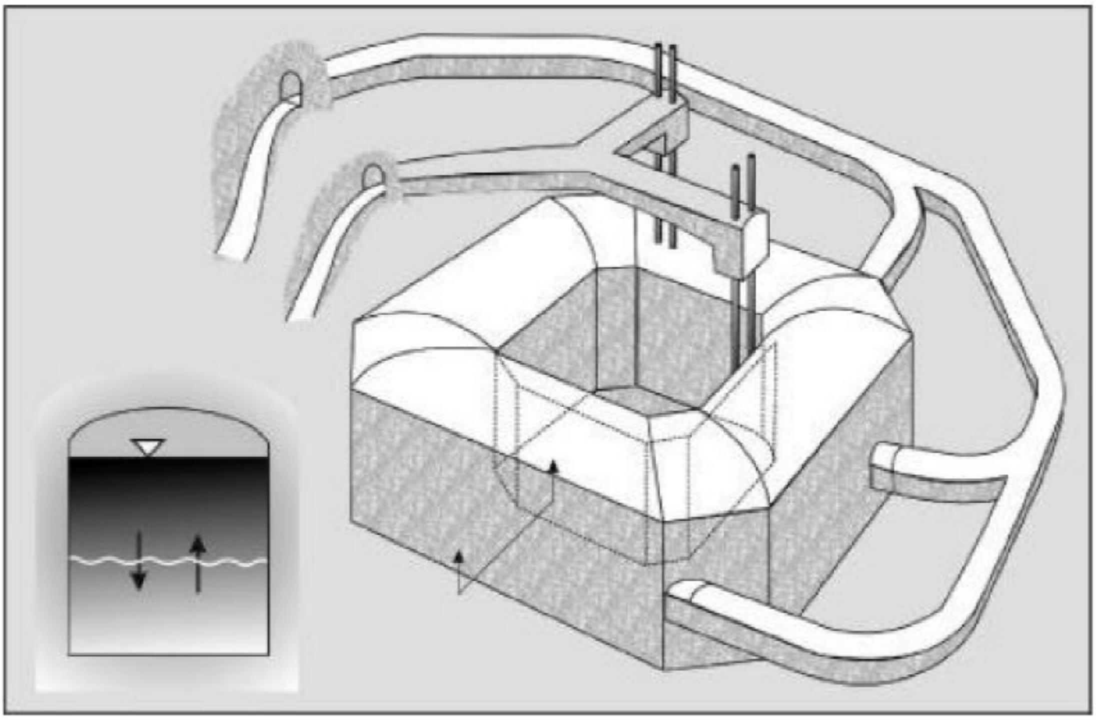


Figure 19: Lyckebo CTES system illustration (Nielsen, 2003)

Figure 19 illustrates the toroid shape of CTES system in Lyckebo Sweden. Lyckebo storage has volume of 104300 m^3 and it has storage capacity of 5.5 GWh (Hellström, 2011). Lyckebo storage was built 1982 and it does not have the optimal aspect ratio that Park, et al. (2014) recommended.

2.6.1 Kerava solar village

In Finland there has been one pilot project for a solar village, Kerava solar village located 30 kilometers north from Helsinki at Savio, Kerava. This project was launched by SITRA at January 1979 by starting a pilot survey of local heating systems that mainly use solar energy for heating. This preliminary survey was completed in October 1979 and in it was presented in it to build a neighborhood of 44 houses that get 75 % of their heating energy from solar energy. Remaining 25 % would be produced with electricity or district heating.

This goal would be achieved with solar collectors and seasonal energy storing. (Lund & Mäkinen, 1982)

Other goals to achieve with this project was to find economically profitable solution for seasonal storing so that solar collectors can be used also with old district heating networks and to find out information on the costs for contractors. Pilot survey demonstrated that projects economical profitability would be poor. (Lund & Mäkinen, 1982)

Technical solutions at Kerava solar village

Heat center with thermal energy storage was located at the middle of the neighborhood. TES is done with two component storage that has 1500 m^3 water tank excavated to the bedrock and a borehole heat exchange (BHE) system is drilled around the water tank. Purpose of this BHE is to capture the escaping heat from the water tank, see Figure 20. Water tank has diameter of 10 meters and depth of 21 meters. Bottom of the water tank is excavated into shape of a funnel. BHE is constructed by drilling 54 boreholes around the water tank with same distance of the center of the tank. Boreholes are drilled into two different angles creating two separate rings of boreholes. The boreholes were mainly used for heating the cold water returning from vaporizer of heat extractor before it was returned to the storage tank. (Kauppa ja teollisuusministreriö, 1986)

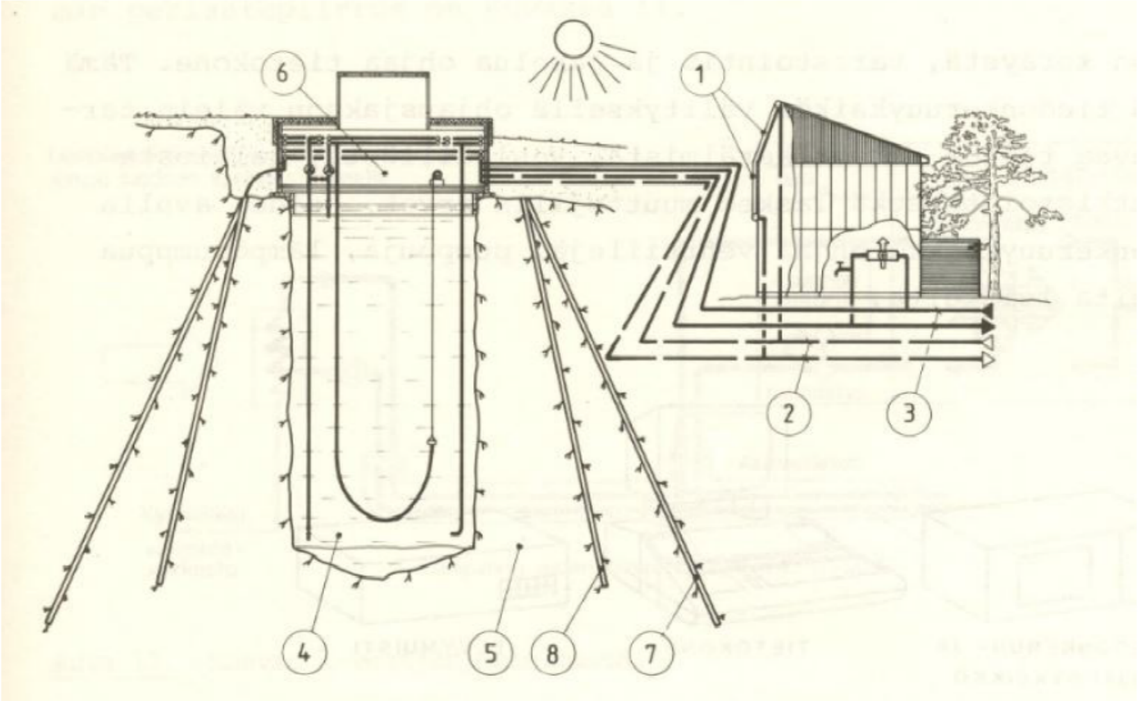


Figure 20: Storage system of Kerava solar village. 1. Solar collectors 2. Pipe system circulating water-glycol mixture 3. Pipe system for district heating 4. Water tank 5. Rock storage 6. Heating center 7. Outer circle of boreholes 8. Inner circle of boreholes (Lund & Mäkinen, 1982)

Water in the storage is stratified so that warm water is always located at the top of the tank and cool water is always located at the bottom. Energy efficiency of the solar collectors is boosted by circulating cool water from the bottom to the solar collectors. Water temperature at the top of the tank is maintained at minimum of 50 °C. If this minimum temperature is not achieved with solar collectors it can be heated with electric boiler using cheaper night time electricity. (Lund & Mäkinen, 1982)

Solar energy is collected with solar collectors that have combined surface-area of 1100 m^2. Collectors are located on south facing walls and rooftops. Solar collectors use mixture of 50 % water and 50 % glycol as heat transferring fluid. Collected solar energy is transferred to heat storage by heat extractor that is located in the heating center. Water returning from solar collectors is mixed with water returning from heat exchanger that is used for heating the houses. This returning water mixture is pumped to correct layer of stratified water by using a winch that is controlled by computer. (Lund & Mäkinen, 1982)

Kerava solar village was monitored during years 1983 – 1985 which year 83 was spent getting systems running and during year 85 there were major problems with the heat pump so year 84 is the only year with comparable results. During these years TES has shown excellent energy efficiency of 85 %. This means that 85 % of the energy that is charged into the system is also dischargeable from the system. The BHE system is capturing 40% of escaping heat grows the energy efficiency figure by 10 percentage points. Solar collectors were able to collect 30 % of the solar energy that hit the collector surface. That is equivalent of 250 – 280 kWh/m^2 annual production. This is typical value for this type of solar collector. (Kauppa ja teollisuusministreriö, 1986)

Actively collected solar energy provided 30.8 % of heating demand and passively gathered solar energy provided 7.2 % equaling solar fraction to be 38 %. KERCONT simulation program was used for researching effect of different arrangements to Kerava solar village self-reliance ratio. Final report of Kerava solar village suggest that by making these modifications to the system process could be improved:

- Changing control parameters of the process by seasons could improve self-reliance ratio by 4 – 5 %

- Not mixing returning water from heat exchanger and solar collectors by equipping solar circuit with own winch at water storage tank could improve self-reliance ratio by 11 %
- Replacing current solar collectors with more efficient models could improve self-reliance ratio by 10 %
- Making storing of solar power more efficient by increasing the size of the water tank storage tenfold could improve self-reliance ratio by 26 % (Kauppa ja teollisuusministreriö, 1986)

Major problem with Kerava solar village was the size of the energy storage. The annual amount of solar energy that was provided by solar collectors was ranging between 250 – 350 MWh and the seasonal storage had only capacity of 250 MWh. This would lead to a situation where the storage is fully loaded before end of the summer and all the energy that cannot be stored is wasted. Also more efficient usage of BTES system should increase the solar fraction. (Kauppa ja teollisuusministreriö, 1986)

2.6.2 CASE: Heat storage cavern in Oulu

Kemira Oy is producing waste heat in form of water heated to 100 °C as a by-product of their main process. This waste heat is sold as thermal energy used in a district heating system in city of Oulu. This waste heat is produced all year round with power of 10 MW and before the CTES system this excess heat was pumped to Oulu River during summer months. Kemira Oy had been using industrial petrol in their process of making ammonia but this usage has stopped due risen prices of petrol. After this decision storage caverns for the petrol became useless. This storage has two main caverns with volume of 95000 m^3 each. Figure 21 illustrates the shape of the storage. This storage cavern was modified to work as a CTES system. This system is used for seasonal storing and for short term storing (Ritola, 1990). According to Alanen, et al (2003) Oulu cavern is still in use.

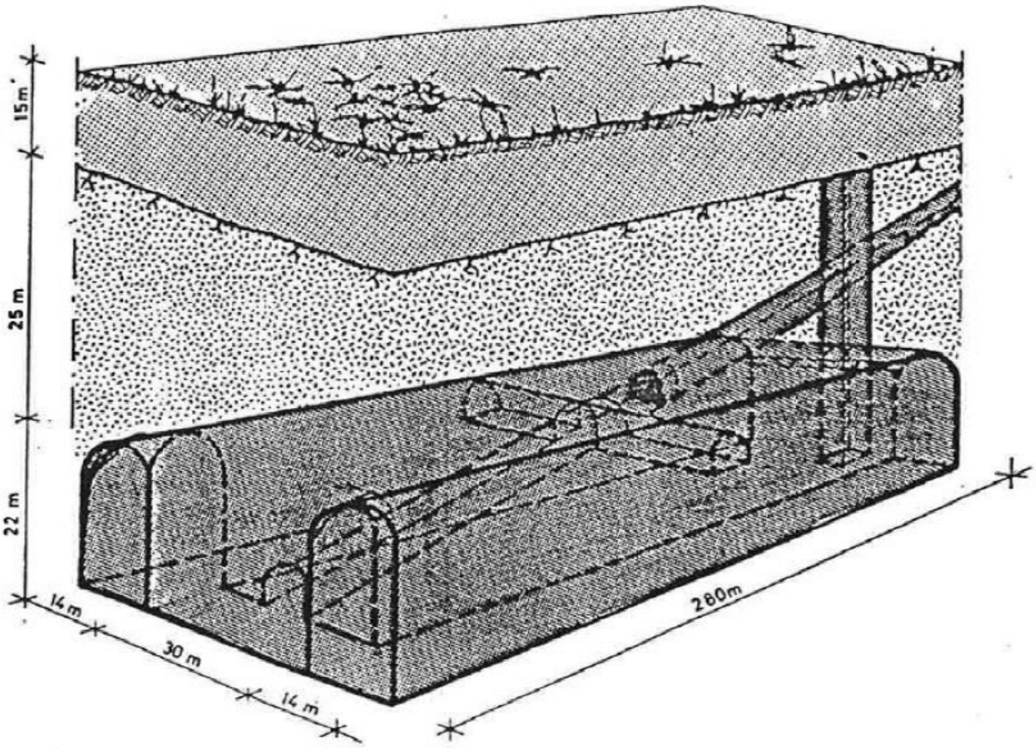


Figure 21: Schematic picture of CTES system in Oulu (Sipilä, 1989)

Table 5: Technical values of Oulu heat storage after (Sipilä, 1989)

Storage volume	190000	m^3
Storing temperatures		
Maximum	115	°C
Minimum	50	°C
Effective storage temperature range	65	°C
Theoretical storage capacity	14.3	GWh
Loading / extracting power	100	MW
Annual heat losses with seasonal storing		
Calculated values	1st year	30 %
	3rd year	21 %
	5th year	17 %

Table 5 illustrates theoretical storage capacity with 65 °C temperature difference is 14.3 GWh. This storage capacity with 100 MW extraction power will last for 143 hours which is 5.96 days.

With the seasonal storing the bedrock will also store part of the energy. According to heat conductivity simulations done by VTT geotechnical laboratory 2 – 3 meters of rock can be used as heat storage media. With storing temperatures exceeding 100 °C the storage cavern must be pressurized to prevent water from boiling. Storage in the Oulu case is planned to be pressurized between 200 – 400 kPa and with that pressure water can be stored in temperatures up to 120 °C. (Sipilä, 1989)

2.7 Tank thermal energy storage TTES

Tank thermal energy storage TTES is a method that uses man made water reservoirs to store energy. Tank can be located either above the ground or be buried underground. Tanks can be built from pre-made sandwich-elements, by in-situ casting or, steel. Usually a steel lining is installed inside the water tank to make the storage steam and water tight. (Schmidt & Miedaner, 2012)

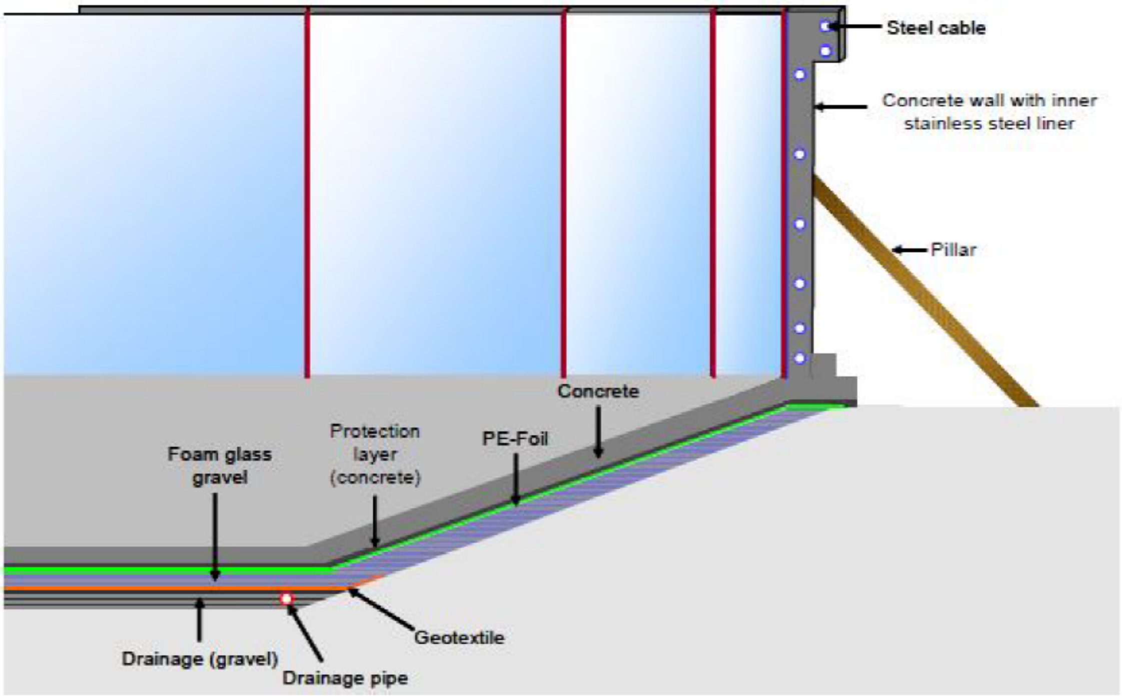


Figure 22: Cross-section with structural details (Schmidt & Mangold, 2006)

Figure 22 and Figure 25 illustrates the structure of TTES system. In the middle of the storage is piping system that can inject or withdraw water from different heights. This ensures that thermal stratification is not disturbed while charging or discharging thermal energy from the system. Surroundings of the tank are insulated to minimize the heat losses by convection to surrounding environment. Walls are made of concrete elements with inner stainless steel liner that keeps the storage water and vapor tight.

Yang, et al (2015) experimented with ten different storage tank shapes and came into conclusion that storage shape is affecting the efficiency of TTES. The shapes that were tested were cylinder, sphere, cone, truncated cone, ellipsoid, spindle, barrel, cylinder + sphere, cylinder + truncated cone, and cylinder + cone.

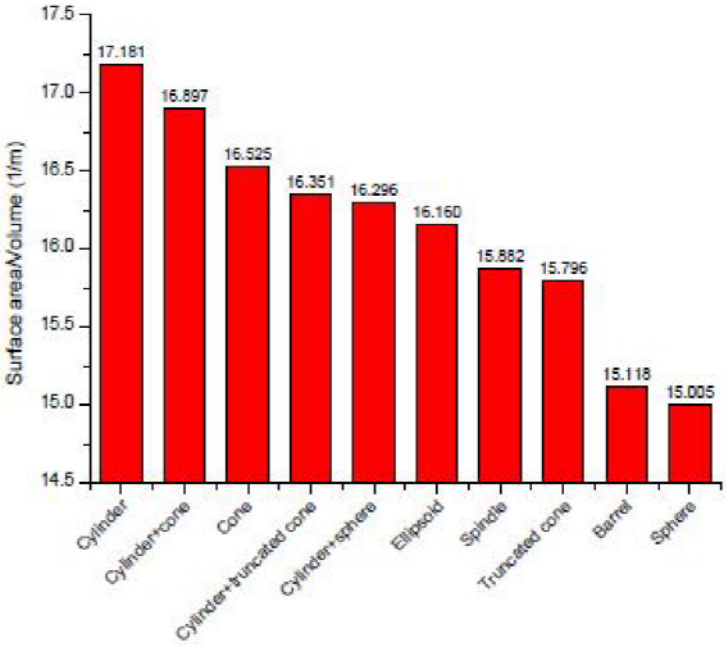


Figure 23: Surface area to volume ratio of different tank shapes (Yang, et al., 2015)

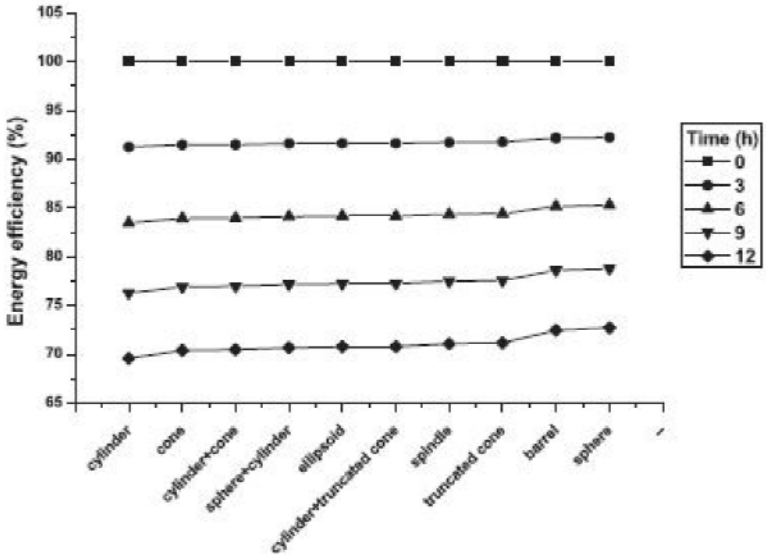


Figure 24: Energy efficiency of different shapes of TTES (Yang, et al., 2015)

Thermal energy losses are caused by two main factors in TTES systems. First one is the mixture of hot and cold water and the second one is heat losses by convection to the surrounding environment. The tests illustrated that main factor that caused differences between different shapes were their surface area to volume ratio. Smaller the ratio is the more efficient the storage is. In the tests barrel and sphere had best energy storing efficiencies and the smallest surface area to volume ratio. Figure 23 illustrates the ratios of different storage shapes. Figure 24 illustrates energy efficiencies of different storage shapes as function of the time.

2.7.1 CASE: Tank thermal energy storage in Münich

Hydro-geological conditions of the Münich site were unfavorable for all other storage methods than TTES as the groundwater level is high and the flow is substantial. For these reasons TTES was chosen to be the storage method. The storage is built on bottom that is in-situ concrete. Storage walls are concrete elements that have steel lining. The wall elements are stressed by steel cables after installation. Figure 22 and Figure 25 illustrates the structural details of the storage tank. The tank is insulated on the top and side walls by expanded glass granules and the bottom is insulated with foam glass gravel for higher stability against static pressure than expanded glass granules. The storage was covered with soil after completion of the building phase for additional insulation and for environmental reasons. The hill that was formed when covering the tank is now in recreational use. The storage has total volume of 6000 m^3 but only 5700 m^3 is in use and the 300 m^3 is left for thermal expansion. (Schmidt, et al., 2011)

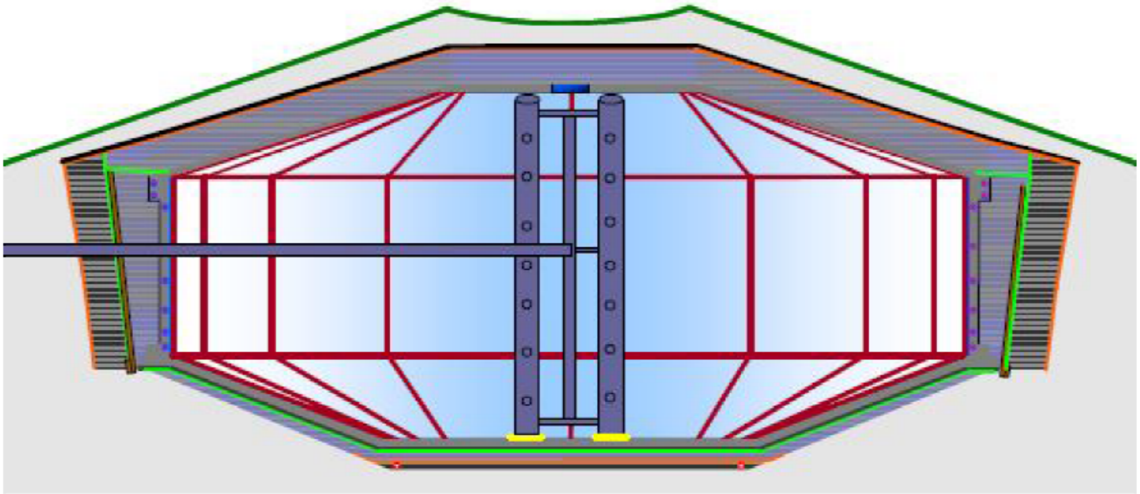


Figure 25: Cross-section of TTES in Münich (Schmidt & Mangold, 2006)

2.8 Pit thermal energy storage PTES

The basic idea behind PTES system is to excavate a large pit into the ground and fill it with water. This large water reservoir acts as the storage media for stored heat. Idea behind PTES is very similar to TTES but the main difference is that the storage walls are natural material and have no supporting structures as the pit is excavated to soil or hard rock.

Inclination of the slopes is usually limited to 1:2 for practicality reasons of lining installation. Usually the pit volume is increased by using the excavated soil from the bottom on the side embankments. (Dannemand & Bodker, 2013)

Figure 26: Excavated slopes at SUNSTORE 3 storage in Dronninglund. (Jensen, 2014)

2.8.1 Lining of PTES

The pit has to be made waterproof to prevent leakage as the escaping water is reducing the storage volume and the energy that was stored in the escaping water is also lost.

In Denmark a clay membrane at Ottrupgård pit was tested to prevent the leakage but that idea did not work properly. It was designed so that a little amount of water would leak trough the clay membrane to prevent it from cracking. However the leakage was too severe and the pit had to be emptied. Bentonite lining was applied and it did reduce the leakage from 6 m^3 a day to 1.6 m^3 a day for a short time. The loss of water has increased since to value of 3 m^3 a day. (Jensen, 2014)

Nowadays polymer, elastomer and metal liners are used to make the pit watertight. Polymer and elastomer liners have price advantage over metal liners but metal liners have advantage on long term stability and vapor tightness. Lining of SUNSTORE 3 can be seen in Figure 26. (Jensen, 2014)

2.8.2 Floating cover

The most expensive part of the PTES system is the floating cover that is insulating the top of the PTES. There are three basic types of floating covers:

- Flexible insulation mats that consist of watertight floating liner and a top liner. Flexibility allows the liner act as a single unit that covers the whole storage area and it is able to move along with the changing water surface level.
- Stiff insulation elements that are either floating on top of the water or they are insulated between watertight liners; usually the insulation material cannot withstand direct contact with hot water for a long time.
- Cover based on a bulk installation of insulation material e.g. expanded clay or expanded glass balls that are contained between watertight insulation liners. The expanded clay cannot withstand direct contact with water as it loses its insulating attributes.

All cover types are structured in a way that they cannot take heavy load on them and this results into that the area of the PTES is not usable for anything else than store energy.

2.8.3 PTES system filled with gravel

A solution for a load bearing lid structure is to fill the pit with mixture of gravel and water so that the gravel supporting the lid by moving the loads to sides and bottom of the pit. This way the pit has to have 50 % greater volume to store same amount of heat as the pit with water only (Schmidt, et al., 2004). Pits are usually covering a large area so that is useful to get this area to be used as a park or something else that is upgrading the area.

2.8.4 CASE: SUNSTORE 2, 3 and, 4

Marstal, SUNSTORE 2 was built during year 2003. It has 10000 m^3 of storage capacity. The pit storage was an upgrade from the Ottupgård PTES. Because of the lining problem with the clay on top of the ethylene propylene diene monomer (EPDM) liner was replaced with a liner made from polyethylene (PE) without the clay. Lid structure was altered so that the level of the lid was fixed. Purpose of SUNSTORE 2 was to experiment with a structure that could reduce costs of an over 50000 m^3 PTES systems to under 35 € / m^3. Cost of SUNSTORE 2 was 670000€ so it fell far behind from the goal of higher capacity pits with construction costs of 67 € / m^3. The SUNSTORE 2 is still running today with storing capacity of 638 MWh. (Jensen, 2014)

Marstal, SUNSTORE 4, built during 2011-12, is a PTES system with 75000 m^3 of storage capacity. It is a development of SUNSTORE 2 project. The goal of construction costs being under 35 € / m^3 was almost met as costs were 35.7 € / m^3. (Jensen, 2014)

Dronninglund, SUNSTORE 3, built between 15th March 2013 and April 2014 is a PTES system with storage volume of 60000 m^3. Solar collectors cover 37573 m^2 area having maximal power of 26 MW. Heat exchanger is a 2.1 MW absorption heat pump. (PlanEnergi, 2015)

The pit is excavated into an old gravel pit and the groundwater level is 3 meters below the bottom level of the pit. This is an optimal location for a PTES system as the groundwater is below the bottom level and rainwater drains trough the gravel layer quickly. Bottom and walls of the pit are covered with 2.5 mm thick poly ethylene liner which has warranty of 20 years if temperatures remain below 90 °C. The floating cover follows the surface level of water during annual fluctuations. Center of the cover is lower than the edges so the rainwater flows to the center. Pumping system pumps the rainwater out centrally from the center. (PlanEnergi, 2015)

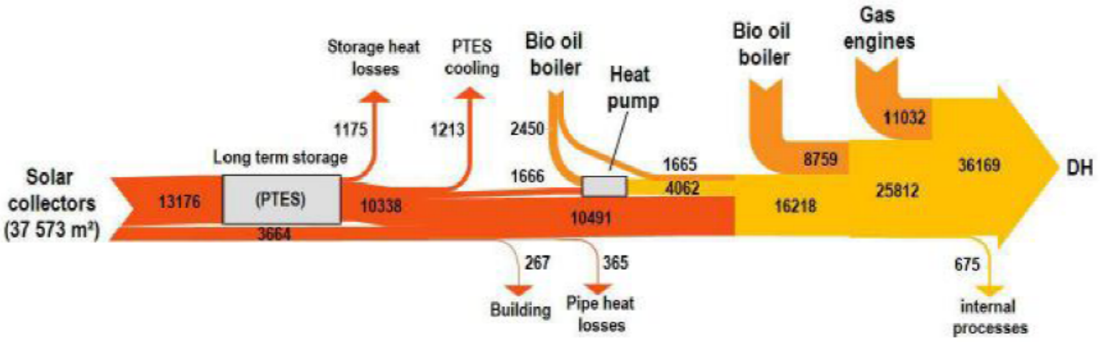


Figure 27: Monitored results from SUNSTORE 3 [MWh/a] (PlanEnergi, 2015)

Figure 27 illustrates the energy flow diagram of entire Dronninglund district heating plant. The PTES system is loaded with 13.2 GWh of thermal energy and 10.4 GWh of it can be discharged to district heating network. This gives the SUNSTORE 3 PTES efficiency level of 78 %. Table 6 has the building costs listed. As the storage volume is 60000 m^3 the price of one cubic meter comes down to 38.10 €.

Table 6: Costs of the Dronninglund PTES after PlanEnergi (2015)

Storage excavation and landscaping	673 000 €
Storage, membrane	1 263 000 €
Heat exchanger, pumps, valves, piping and in- and outlet for storage	350 000 €
Total	**2 286 000 €**

2.9 Combining thermal energy storing methods

Nordell et al. (1994) published a feasibility study for combining advantages of cavern storage and borehole storage. This combination is referred as combi storage. In this study they suggested that two caverns would be connected by series of boreholes. Different storage configurations were designed and evaluated.

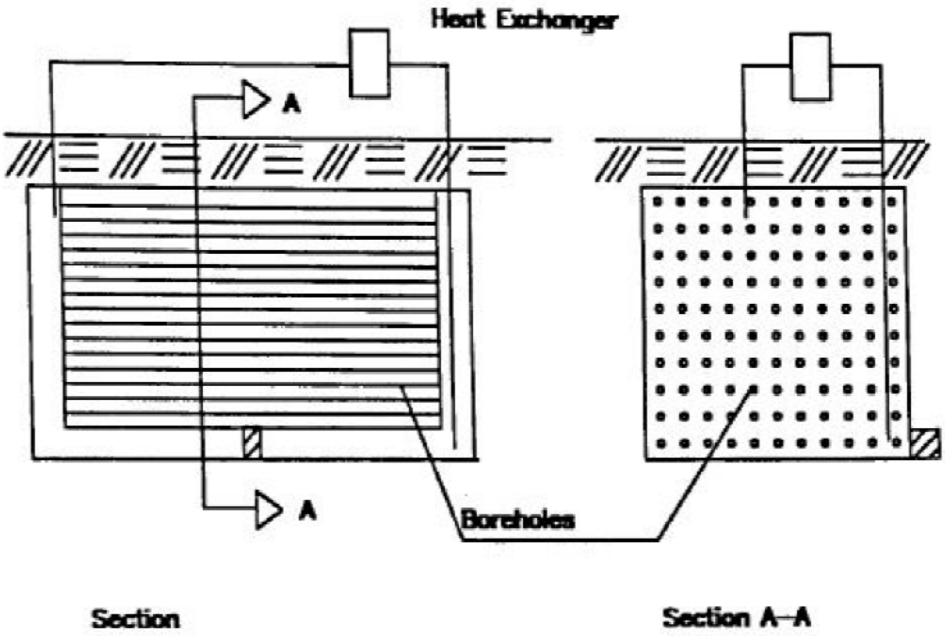


Figure 28: Cross-section of combi store model with horizontal boreholes connecting two separate caverns (Nordell, et al., 1994)

The best configuration was chosen to be model with two caverns and horizontal boreholes connecting these caverns. Figure 28 illustrates cross-section of this model where hot water is injected on top of the other cavern and cold water is pumped out from the bottom of the other cavern. This causes thermal stratification not only in caverns but in the borehole part of the storage also (Nordell, et al., 1994). After construction costs and available methods for excavation and drilling had been considered storage configuration illustrated in Figure 29. This kind of combi storage was planned to be built either in Finland or Sweden, but the pilot was never built.

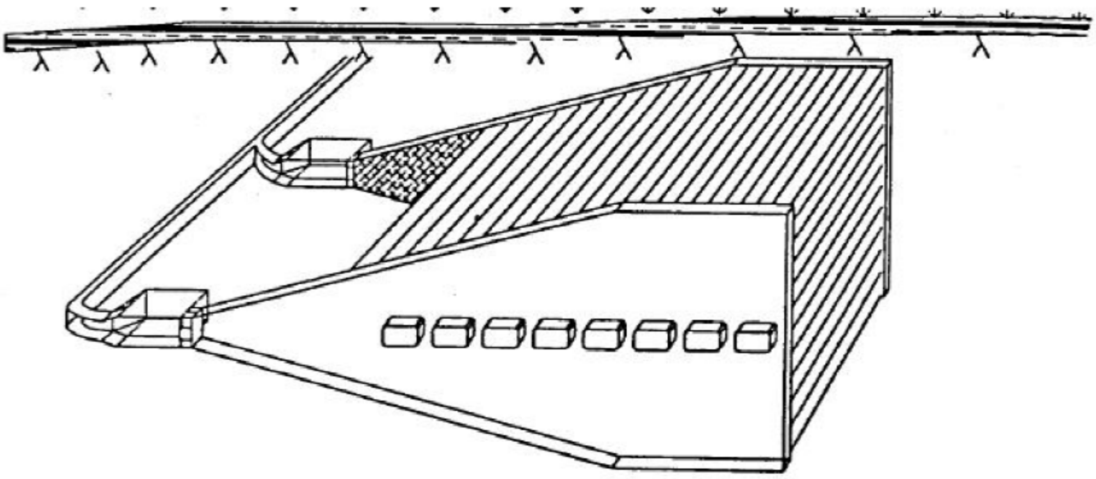


Figure 29: Suggested configuration for combi storage (Nordell, et al., 1994)

Kerava solar village had a water storage that was surrounded by borehole heat pumps that utilized escaping heat from water reservoir. That was not a combi storage but it was an inventive way to increase the amount of solar energy usage. At Attenkirchen, Germany, this concept has been developed bit further. Residential area of 20 single houses and 5 semi-detached houses has a 500 m^3 underground water tank as short term storage and a borehole field of 10500 m^3 drilled into soil surrounding the water tank. Soil heat capacity at the site is 2.7 MJ $m^{-3}K^{-1}$. This makes the BTES system have same heat capacity as 6800 m^3 of water (Reuss, et al., 2006). Configuration of Attenkirchen storage can be seen in cross-section in Figure 30.

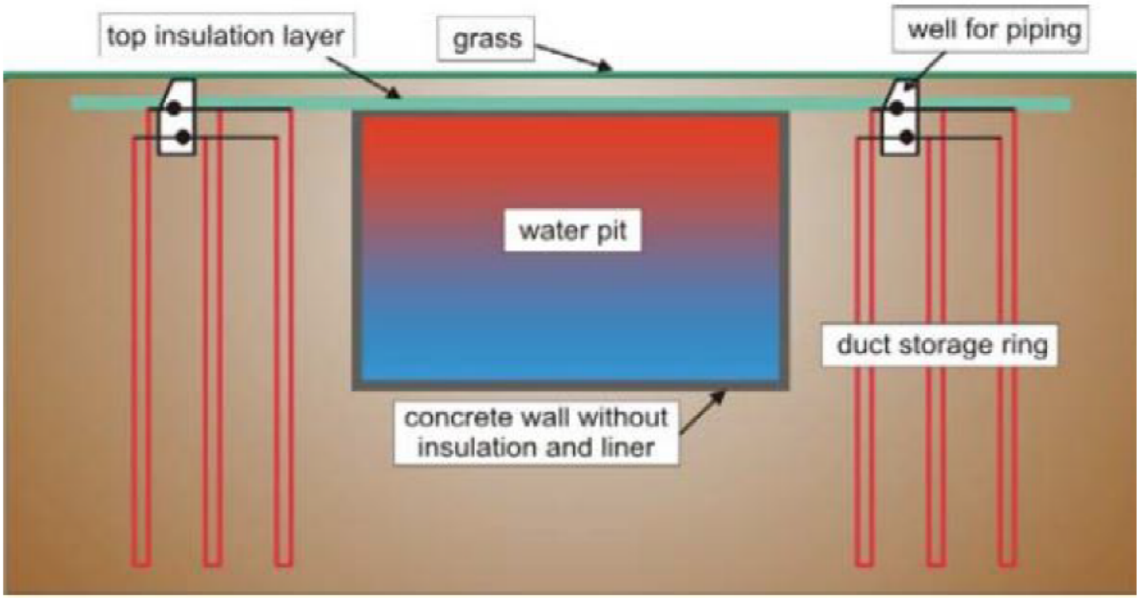


Figure 30: Cross-section of Attenkirchen combi storage system (Reuss, et al., 2006)

The building costs of the tank are decreased by not insulating the tank. The surrounding BTES system benefits from the heat losses from the tank. Table 7 illustrates the building cost of the combi storage system. Reason for building an expensive water tank is that the heat cannot be extracted from soil quick enough to fulfil the heating energy demand.

Table 7: Building costs of Attenkirchen thermal energy storage

	Volume [m^3]	Volume water equivalent [m^3]	Cost [€ m^{-3}]	Cost water equiv-alent [€ m^{-3}]	Total cost [€]
Water tank	500	500	406	406	203200
BTES	10500	6800	12	18	124100
Total		**7300**		**45**	**327300**

3 Evaluating UTES for Solar Community concept

3.1 Criteria for UTES evaluation

Dincer & Rosen (2010) lists criterions that should be taken into consideration when planning a UTES system. This listing has been modified by removing irrelevant parts for Solar Community Concept (SCC) project. This listing is presented in Figure 31 and subchapter 3.2 will evaluate different thermal energy storage methods and their feasibility for the SCC based on this listing.

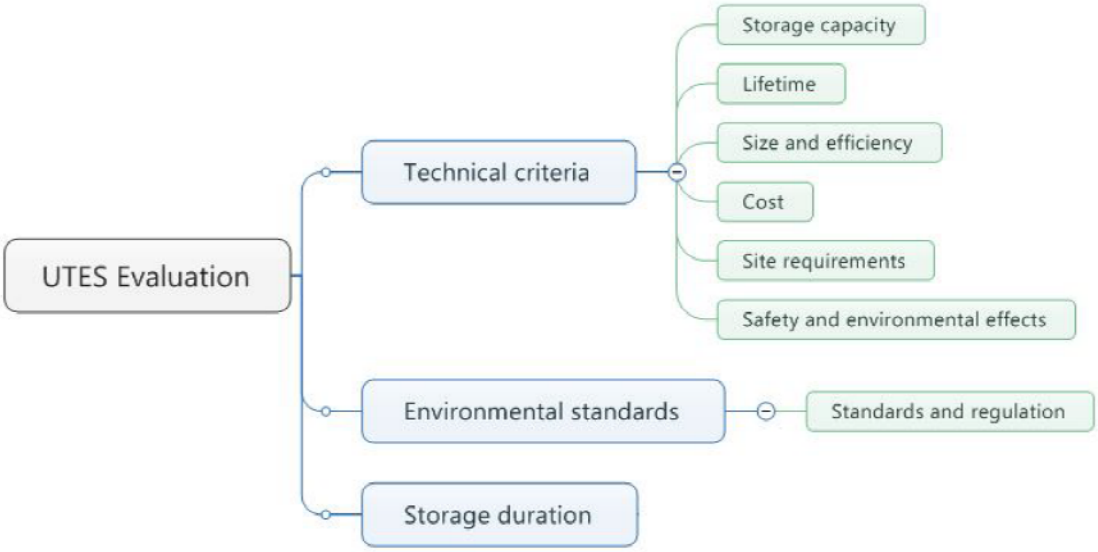


Figure 31: Evaluation criteria for UTES system after (Dincer & Rosen, 2010)

Figure 31 illustrates evaluation criteria for UTES system evaluation. The most crucial aspects that define the UTES type are storage duration and the amount of energy that is discharged from the storage. Storage duration defines that how long is the time period of energy storage, and how quickly the storage must be able to deliver the demanded energy. Higher the thermal conductivity, faster the discharging rate. Short term storages demand high thermal conductivity whereas seasonal storages can be implemented with lower thermal conductivity values.

When the amount of demanded heating energy is known storage capacity can be calculated by knowing the efficiencies of different storing methods. Different storing methods have different amounts of heat losses and this affects the amount of energy that must be stored into the storage to get the demanded amount of energy discharged. Size of the storage is defined by thermal capacity of storage media and the required amount stored energy. The lower the heat capacity, the higher is required storage volume.

Site requirements may exclude some of the storage methods if the site is chosen before the storage method, and sometimes the chosen site may offer advantageous opportunities for one storage method. Example for this kind of advantage is a rock cavern that can be modified cost effectively into an UTES.

Safety and environmental effects must be taken into consideration when choosing UTES system. Heat losses from the storage increases temperature of storages surroundings. When the energy is stored in groundwater as in ATES system increasing groundwater temperature might alter the pH of the groundwater and cause changes in its chemistry.

Cost of the storage is also a major part of the UTES evaluation, as one of the main goals of energy storing is to be cost effective as possible. Some of the UTES methods are suitable for only small scale seasonal storing whereas some of the methods become economically feasible only in large scale.

3.2 UTES evaluation for the SCC case

This chapter evaluates UTES methods for SCC case using the criteria represented in the chapter 3.1. The goal is to find a storage solution that provides most cost efficient way to store solar energy.

3.2.1 The Finnish environment

Finnish climate

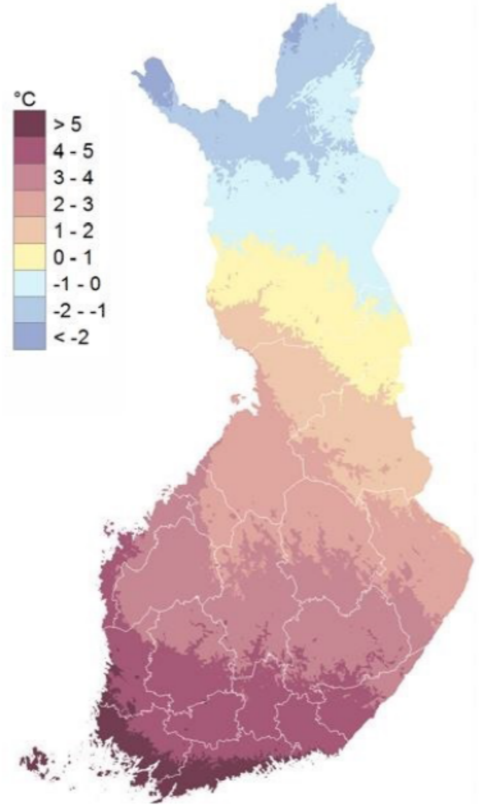


Figure 32: Average temperatures in Finland during 1981 – 2010 (Ilmatieteen Laitos, 2014)

Figure 32 illustrates average temperatures in Finland. Southern Finland is noticeably warmer than northern parts of Finland. This difference can be perceived in amount of heating degree days in different areas of Finland. Heating degree days are calculated by adding the difference between indoor and outside temperatures of the whole year. Annual heating degree days are in Helsinki 3878, Oulu 5057 and, Ivalo 6231. (Ilmatieteen Laitos, 2015)

Finnish ground conditions

Finland is located on the Fennoscandian shield. Crystalline Precambrian bedrock is stable and thus suitable to be used in energy storing purposes. Stable bedrock is mandatory when building large storage caverns.

Kukkonen and Peltoniemi (1998) measured thermal properties in Finnish rocks. In most rock types the mean thermal conductivity is between 2 – 4 W m^{-1} K^{-1}. The mean value of all samples were 3.24 ± 1.00 W m^{-1} K^{-1}. This value is controlled by the mineral composition of the rock, but also by rock texture, rock porosity and, pore filling fluids (Kukkonen & Peltoniemi, 1998). Specific heat capacities of the individual minerals and the relative amounts of these minerals control the heat capacity of the crystalline rock. Typical range for crystalline bedrock is between 770 – 830 J kg^{-1} K^{-1} (Kukkonen & Lindberg, 1998).

According to Soininen (2013) thermal properties of soil depend greatly on how porous and saturated the soil is and on the minerals that soils contains. Highly saturated porous soil has totally different thermal properties than highly porous dry soil as the air is acting as an insulator and the water as conductor. Table 8 illustrates thermal properties of different components that constructs soil.

Table 8: Properties of soil after (Huang, et al., 2012)

Soil constituent	Density [kg m^{-3}]	Specific heat [kJ kg^{-1} K^{-1}]	Conductivity [W m^{-1} K^{-1}]
Quartz	2660	0.75	8.8
Clay minerals	2650	0.76	3
Soil organic matter	1300	1.9	0.3
Water	1000	4.18	0.57
Air	1.25	1.0	0.025

Average soil layer thickness in Finland is 8.5 meters but it can reach values up to 100 meters. Thickness of soil affects the storage method selection as thick soil layer may prevent some of the TES methods being feasible. For example CTES system cannot be built in area where the soil layer is thick as reaching the bedrock would be extremely expensive. The groundwater level in Finland is located usually in depth of 1 – 4 meters from the surface, but it can be located as deep as 20 meters in ridges and bedrock (GTK, 2005). The groundwater flow can cause heat losses for the storages that are in direct contact with the groundwater if the flow is substantial. The crystalline bedrock can have roughness zones that have groundwater flowing through fractures causing heat losses. Most of the Finnish bedrock is unbroken and has little to none groundwater flow.

Insolation levels in Finland

According to NASA (2015) the yearly average insolation in southern Finland is 2.73 kWh/m^2/day. Although the yearly average is misleading as the SCC project will be only collecting solar energy from May to August and during those months insolation levels are greatly above average levels. Reason for not including April or October into collecting months is that in most years these months are ones that require heating energy from the seasonal storage. Technically there is no obstacles to begin collecting during April and continuing collecting during October if warm weather allows it. Figure 33 illustrates average monthly insolation levels at Helsinki. During those summer months one square meter that is tilted 45 degrees collects average amount of 4.99 kWh per day. This value could be enchanted to 5.23 kWh per day by changing the collector angle to most optimal every month, but this would require the solar collectors to be mounted on a frame that is not a solid structure. This feature would increase the unit cost of collectors greatly. For that reason collectors with fixed frame are more feasible.

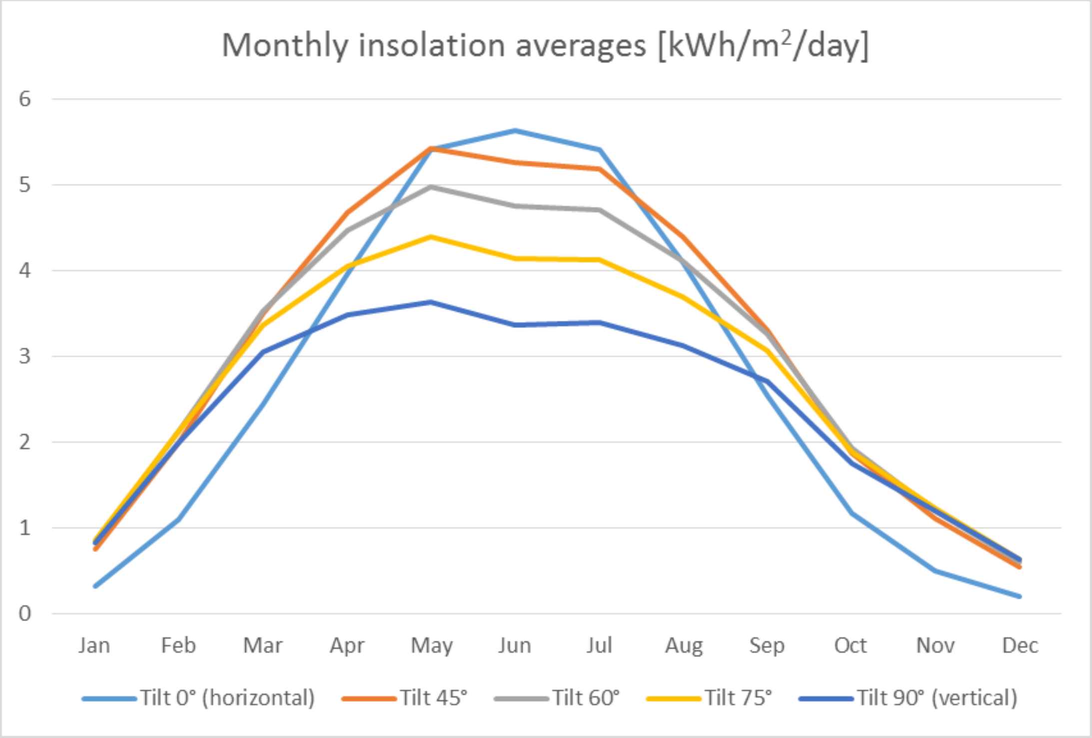


Figure 33: Monthly insolation averages at Helsinki after NASA (2015)

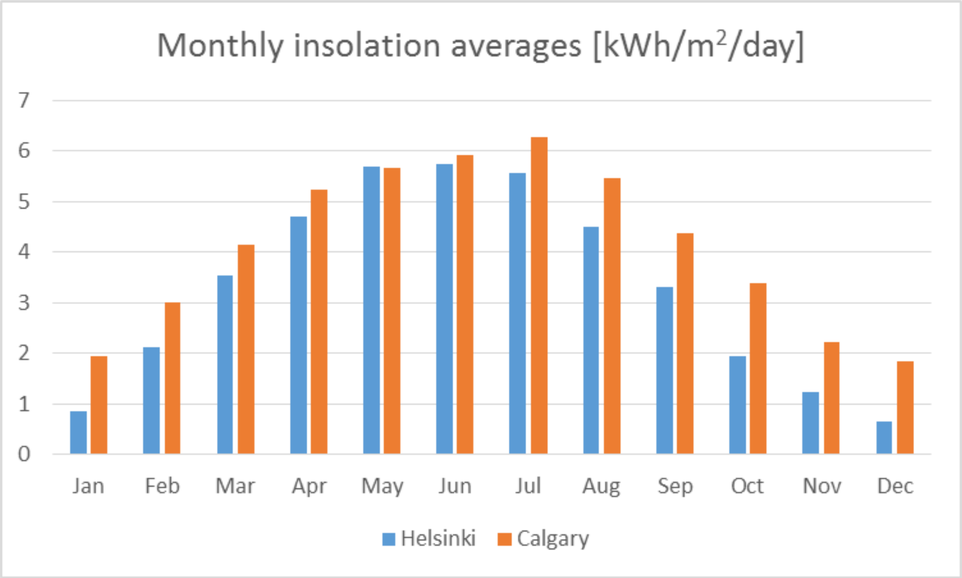


Figure 34: Comparison of insolation levels after NASA (2015)

Figure 34 is a column chart of monthly insolation averages at Helsinki and Calgary. These averages are from optimally tilted solar collectors. It can be seen that the yearly average of Calgary is substantially higher than at Helsinki, but most of that difference comes during months that the solar energy is not collected. This is a promising result as one of the most successful solar community project Drake Landing Solar Community has no substantial advantage in insolation averages during summer months.

3.2.2 Technical criteria

Storage capacity

Preliminary sizing calculations have been done by Hirvonen & Mohan (2015) to give the needed capacity to meet energy demands of the SCC project. SCC village contains 50 houses with floor area of 100 m^2 each.

Table 9: Annual energy demands after Hirvonen & Mohan (2015)

Type	Annual demand [kwh m^{-2} a^{-1}]
Ventilation	5
SPH	30
DHW	40

Table 9 has values that were used in the calculations. It was estimated that demand of domestic hot water (DHW) was covered directly by the solar collectors during the five months of greater insolation and the seasonal storage would provide the heating energy for the other seven months. These values give the annual need for stored energy for DHW

131 MWh. Ventilation and space heating (SPH) combined requires 175 MWh of stored energy annually. This combines into annual heating energy demand of 306 MWh. This amount of energy is required to be extracted from seasonal storage to fulfil heating energy demand of SCC village.

Without losses the required amount of heating energy stored would be 306 MWh. As there is no perfect storage method with no losses the heat losses must be taken into the calculations. Energy efficiency of the storage measures the amount of energy that can be discharged from the storage compared to the amount of energy that is charged into the storage. When the storage efficiency is increased amount of heat losses is decreased and vice versa. When energy efficiency of the storage is 50% half of the energy stored is lost to heat losses and only the other half is available for heating. With this energy efficiency example the solar collectors must provide twice the amount of energy that is required to fulfil the heating energy demand as half of the energy is lost to heat losses. If the efficiency would drop to 25% solar collectors must provide four times the required amount of heating energy as three fourths of the energy would be lost to heat losses. Off course this 25% energy efficiency is just an extreme example and no one should build a seasonal storage that has this major heat loss problems. Figure 35 illustrates the amount of energy that must be stored with different storage efficiencies to achieve the required amount of heating energy that fulfils needs of the SCC village.

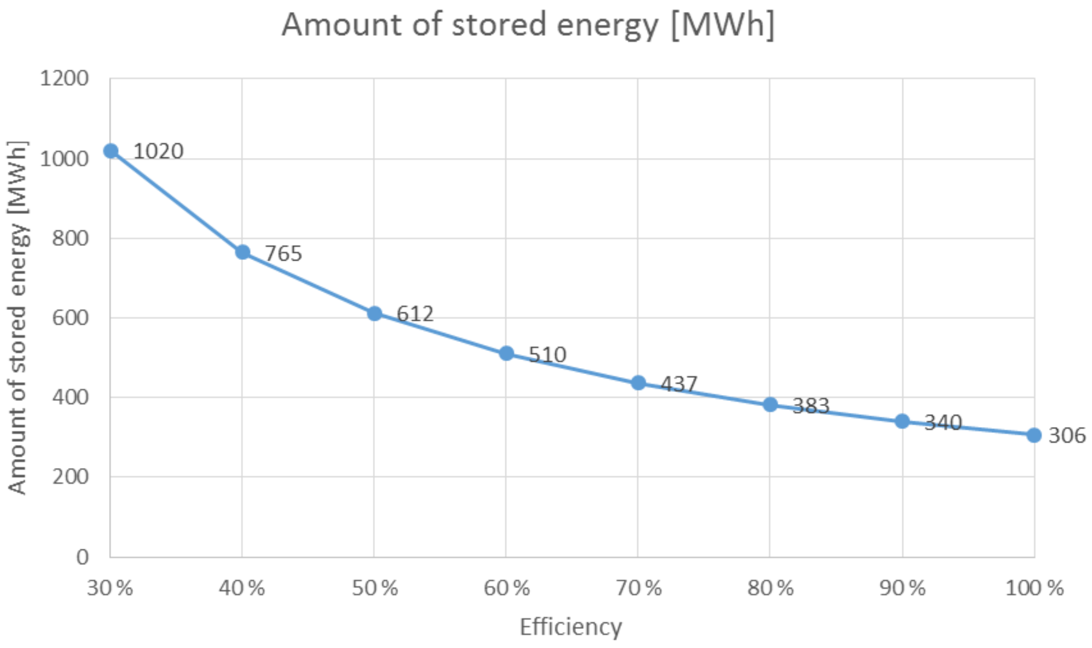


Figure 35: Required amount of stored energy to fulfil SCC village heating energy demand of 306 MWh with different energy efficiencies

Size and efficiency

The volume of storage needed to store constant amount of energy varies between different storage mediums. Also the heat losses vary greatly between different thermal energy storage methods. This leads to that the physical size of the storage that is used in the SCC project varies greatly.

Also the demand of surface area that cannot be used for anything else than energy storing purposes ranges from little maintenance building to a little lake. This is an important factor at dense urban environments where the cost of land is high.

The storage efficiency is important factor as the energy that is lost in heat losses has to be collected with the solar collectors. Decreasing storage efficiency leads to increasing solar collector area which means increased direct costs and maintenance costs which decreases the economic feasibility.

Thermal energy storages that use water as storage media

A major advantage with methods that use water as storage media is that the thermal properties of water are great for energy storing and these properties do not change between different locations or storage methods. For this reason CTES, PTES and, TTES can be reviewed in a group as their storage media is water.

Required storage volume was calculated using equation 5. Water has heat capacity of 4180 kJ kg^{-1} K^{-1} and density of 1000 kg m^{-3}. Figure 36 illustrates the calculated storage volume with different storage efficiencies and temperature differences.

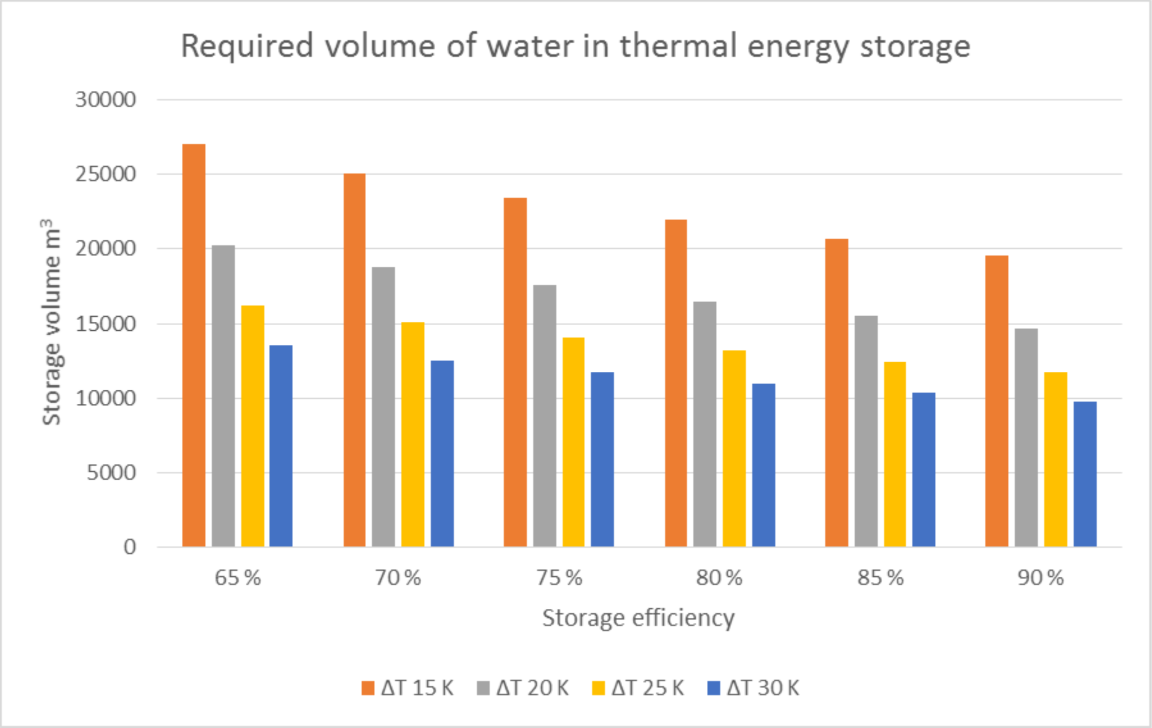


Figure 36: Required storage volume for TES systems that use water as storage media

The reason for the differences in storage efficiencies between CTES, PTES, and TTES is differences in the heat losses. Possibilities and requirements for insulation vary greatly between these storage methods.

Cavern storages have the surrounding bedrock acting as insulation and no additional insulation layer is needed. The disadvantage with bedrock insulation is that it absorbs significant amount of stored energy until it is heated up to same temperature levels as the water inside the cavern. According to Lee (2013) after two years the surrounding bedrock is heated and the storage efficiency can be up to 90 %. Water leakages from cavern to surrounding bedrock and groundwater leakages to cavern decrease the storage efficiency. For this reason grouting must be done with extra caution.

According to PlanEnergi (2015) SUNSTORE 3, 60000 m^3 pit storage, has efficiency of 78 %. As the lining is laid directly on soil slopes without any insulation layer, the floating cover is the only part of PTES system that is insulated. Early PTES projects had problems with the insulation material of the cover and water vapor. Water vapor soaked the insulation material which increased thermal conductivity and added heat losses and thus decreased the efficiency of the storage. Another factor that can decrease the storage efficiency is the groundwater. If groundwater level is above the bottom level of the pit and the heat losses are significantly higher as groundwater conduct heat more efficiently than dry soil.

Tank storages are usually smaller than CTES or PTES systems. Thus the amount of energy stored in tanks is lesser and the proportional heat losses are more significant. According to Nuβricker-Lux *et al.* (2009) Friedrichshafen 12000 m^3 tank thermal energy storage has efficiency of 60 %. One main advantage with TTES is that the whole system can be designed thoroughly. The efficiency percentage can be increased by adding additional insulation layers, but it may not be economically feasible as the same capacity increase might be more feasibly done by increasing the storage volume.

When choosing water as storage media for SCC project the storage efficiency ranges somewhere between 60 – 90 % which would result to storage volume ranging between 14600 - 22000 m^3. Minimum storage volume is attained with CTES which has highest storage efficiency. Cavern could be excavated in a shape of cuboid that has height of 14 m, width of 15 m and length of 70 m. This would lead to a cavern that has volume of 14700 m^3. Roof of the cavern would be excavated into shape of an arch for better mechanical stability and additional space for piping.

Thermal energy storages that use rock as storage media

Borehole thermal energy storage (BTES) is storage method that uses bedrock as storage media. According to Reuss (2015) most of the heat escapes from BTES system through top of the BTES system. This can be reduced with proper insulation layer on top of the borehole field. Proper insulation can be obtained by covering the borehole field with expanded polystyrene (EPS), extruded expanded polystyrene (XPS), or some other cheap and easily installing insulation material, and a layer of porous dry soil. Although the top of the storage will remain the main route for the escaping heat as the rock mass surrounding the storage does not have high thermal conductivity. This leads the surrounding rock mass to act as insulation after it is heated up to same temperature levels as the storage. Most efficient way to reduce the amount of escaping heat is minimize surface-to-volume ratio. This is done by choosing diameter of the borehole field to be roughly the same as the drilling depth of the boreholes.

The required storage volume for a BTES system in granitic bedrock is determined by the temperature change during the discharge phase and by the storage efficiency. Storage volumes were calculated using following equation:

$$\boldsymbol{V = \frac{E}{C_p \rho \Delta T}} \tag{5}$$

Where V = storage volume [m^3]

E = amount of stored energy [kJ]

C_p = heat capacity [kJ kg^{-1} K^{-1}]

ρ = density [kg m^{-3}]

ΔT = temperature difference between water entering the system and water leaving the system [K]

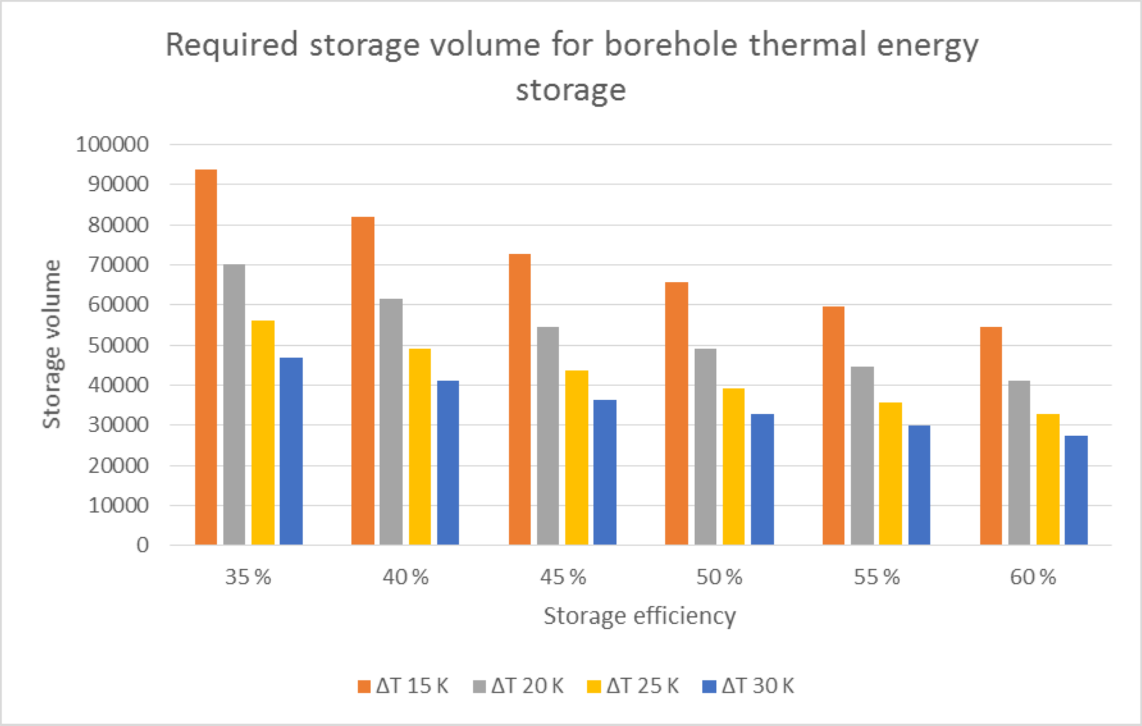


Figure 37: Required storage volume for BTES

Figure 37 illustrates the required storage volumes when the storage efficiency is ranging between 35 – 60 % and the temperature change ΔT is ranging between 15 and 30 K. According to Nordell (1994) granite has heat capacity of 830 kJ kg^{-1} K^{-1} and the density of granite is 2700 kg m^{-3}.

The challenge with this estimation is that as the storage size decreases the volume to surface ratio of the storage also decreases. Decreasing volume to surface ratio leads to greater relative heat losses, which lowers the storage efficiency. Also the greater temperature difference between the storage and the surrounding bedrock leads to greater heat losses. The storage size can be optimized by running computer simulations of different storage sizes and temperature differences. Also the varying size of the solar collector area has to be taken into consideration when finding the optimal storage size as the goal is to find the most inexpensive method to provide the required 306 MWh of heating energy.

Suggested BTES system for SCC project using ΔT value of 20 K with storage efficiency of 40 % has calculated volume requirement of 61 446 m^3. Volume-to-surface ratio is important factor for minimizing heat losses. This can be maximized by making the diameter of the borehole field equal with depth. Shape of the borehole field can also be a factor that greatly affects this ratio. By choosing the shape to be a circle instead of a square surface area of the storage is minimized effectively. By choosing circle the storage will have cylindrical shape and the square will make the storage to be shaped like a cube. Table 10 illustrates the difference in the volume-to-surface ratio between cylindrical shape and cube.

Table 10: Volume-to-surface ratio of cube and cylinder

Shape	surface area [m^2]	Volume [m^3]	Surface-to-volume ratio
Cube	9343	61446	0.152
Cylinder	8620	61446	0.140

When drilling the boreholes with a configuration that has a constant center to center distance between boreholes, options are to drill the boreholes into square or hexagonal pattern. By drilling the holes into hexagonal pattern the center to center distance can be increased by 7.45 % to achieve the same volume of rock as with square pattern. By obtaining the same volume of storage media with less boreholes money is saved in drilling costs.

This can lead to cost savings especially with large borehole fields with hundreds of boreholes.

Thermal energy storages that uses combination of water and rock as storage media

TES system that uses both water and rock as storage media combines the advantages of both storage mediums. Water has great thermal properties, but it lacks structural strength. Rock on the other hand has great structural strength but it lacks the thermal properties of water. When combining these two storage mediums the goal is to upgrade thermal properties of rock only storage by using water as heat transferring fluid that flows freely through rock mass. This water flow charges the rock mass with thermal energy and acts as storage media itself.

ATES is a natural example of a TES that uses both water and rock. Aquifers are ground layers that are saturated and porous. Water that is pumped into hot well heats up both the groundwater and the porous material it flows through. A man made solution is PTES system that is filled with gravel.

The required storage volume for this can be calculated with equation 6, which is modified version of equation 5 that takes into account portions and properties of two different storage medias.

$$V = \frac{E}{(C_R * \rho_R * x_R + C_W * \rho_W * x_W)\Delta T} \qquad (6)$$

Where V = storage volume [m^3]
E = amount of stored energy [kJ]
C_R = heat capacity of rock [$kJ\ kg^{-1}\ K^{-1}$]
C_W = heat capacity of water [$kJ\ kg^{-1}\ K^{-1}$]
ρ_R = density of rock [$kg\ m^{-3}$]
ρ_W = density of water [$kg\ m^{-3}$]
x_R = relative portion of rock in the storage
x_W = relative portion of water in the storage
ΔT = temperature difference between water entering the system and water leaving the system [K]

Figure 38 illustrates different volume requirements for TES method that is suitable for SCC project capacity requirements using rock and water as storage media with 80 % of rock and 20 % of water.

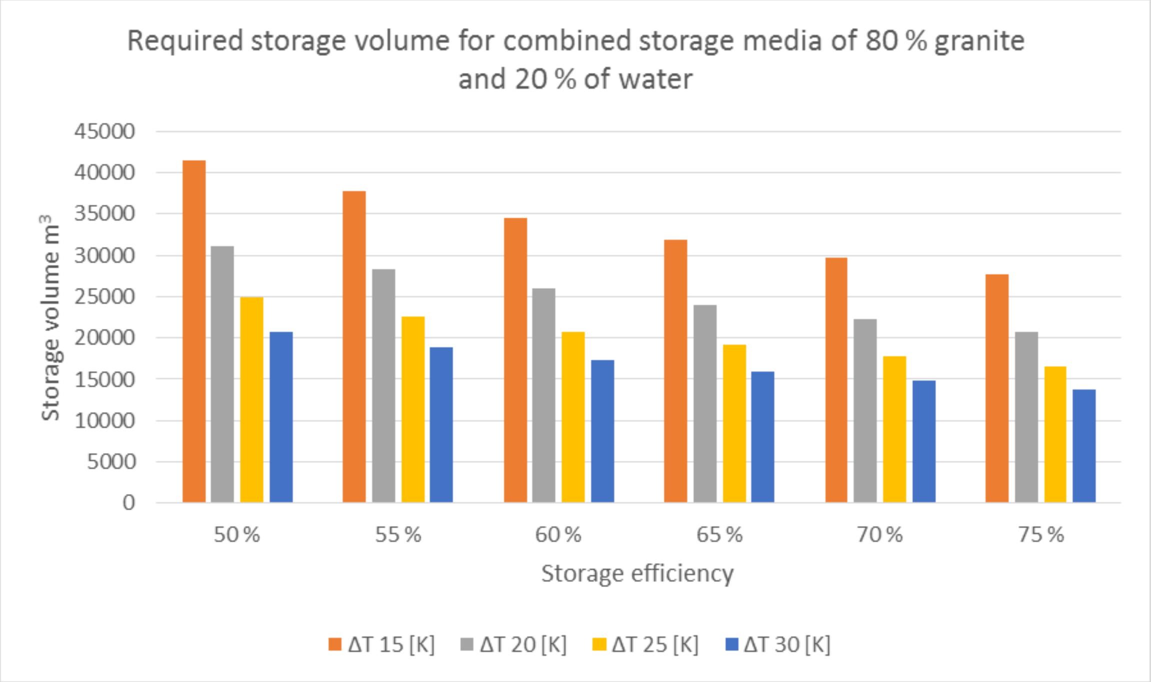


Figure 38: Required storage volume for TES that uses 80 % granite and 20 % water as storage media

Gravel-water pit thermal energy storage (GWPTES) system reaching storage efficiency levels of 65 % would require storage volume of 24 000 m^3 to cover the heating energy demand of SCC project.

Lifetime

Lifetime of TES is depending on parts that are wearing out during usage of the TES. This includes heat pumps, heat exchangers, piping systems, lining and, insulation. Some of the replacements are trivial and some require stopping the whole process of energy storing.

ATES system uses natural water reservoir as storage media, so there is no actual maintenance of the storage itself, but heat exchanger, piping system and, pumps will get worn out. For maximum lifetime expectancy these equipment must be chosen carefully. Chemical properties of the groundwater must be known for choosing materials that are not corroded by the groundwater. The groundwater must be tested regularly when the ATES system is charged to find if there are any changes in groundwater properties caused by thermal fluctuation. Clogging of the wells is also an issue that must be observed as the water yielded from the well is a determining factor for the amount of energy that can be extracted from the ATES.

BTES system uses bedrock or soil as storage media. Heat exchangers are installed into boreholes so there is no maintenance on the storage media itself, but piping system, pumps and, heat exchanger will get worn out. Open system where the heat transferring fluid (HTF) is in direct touch with borehole walls has different criteria for materials than a closed system with heat exchangers that are in grouted boreholes.

With an open system there may some mineral in the bedrock that dissolve when the bedrock gets heated up and HTF is circulating in the borehole. This may affect the water chemistry and cause corrosion to piping system, heat exchanger and, pumps. Also the possible groundwater that may flow through the borehole field may have some corrosive properties.

Closed system has U-pipes installed into boreholes and the HTF is not in direct contact with the bedrock. This solution is advantageous for the heat exchanger and pump as the HTF can be chosen so it has no harmful properties for that equipment. Only part of the heat exchanger system that is in direct contact with the possible groundwater is the piping system. By choosing a suitable plastic piping system there is no problem with corrosion.

CTES system uses water as storage medium and the water is stored in a manmade reservoir cavern. Most vital part for the lifetime of CTES is rock mechanical stability of the cavern. The cavern must be reinforced in a way that allows safe maintenance work inside the cavern if needed. Any maintenance inside the cavern is a major drawback for the storage as the storage needs to be cooled down to a temperature level where a human can work safely. If there is a major leakage of water into or from the storage it needs to be plugged with grouting mass as leakages cause heat loss. Heat exchanger, piping system and, pumps should be placed in a manner that allows maintenance for them as minimal disturbance for the storage process as possible. This could be done by placing these above the ground or in separate cavern.

PTES system uses water as storage media, the water is stored in an excavated pit that is covered with an insulated lid. The pit is made water tight by covering the soil with plastic lining. The lining is rolled out as sheets of plastic that are welded together. These welded seams must be water tight or the PTES system will not work properly. According to Jensen (2014) newly developed high temperature HDPE liners have guarantee of having a lifetime more than 20 years at 90 °C constant. If there is need for repairing or replacing the lining the pit must be drained empty for the maintenance. The floating cover must be designed in a manner that it is vapor proof so the water vapor does not wet the insulation material and decrease the insulating effect of the lid. Heat exchanger, piping system and pumps should be placed in a manner that allows maintenance for them as minimal disturbance for the storage process as possible.

TTES system uses water as storage media, which is stored in a manmade storage tank. The lifetime of the TTES system can be fully controlled by choices in the planning phase as there are no variables that cannot be modified to fit the needs of the storing purposes. By choosing materials with long lifetime and doing regular maintenance work on the heat exchanger, pumps and, piping system the TTES will have a long lifetime.

Cost

SCC is built with economic feasibility goals so the storage must be as cost effective as possible. Cost analysis is widely site specific and required storage volumes may alternate unit costs. Generally storage with greater volume has lower unit costs than a smaller storage as fixed costs such as machinery mobilization are divided by bigger volume. Also some parts can get discount when they are bought in greater quantities. The storage at the SCC project is a rather small scale seasonal storage thus there will not be advantages that can be acquired with a greater storage volume.

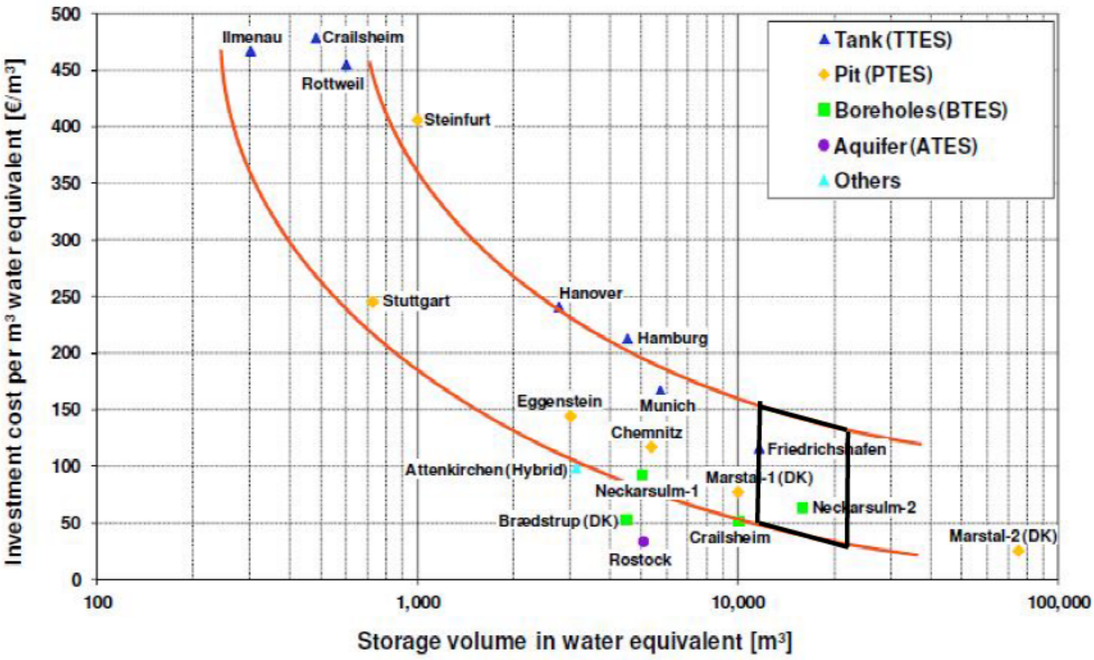


Figure 39: Small scale systems are generally more expensive than their large scale comparisons after (Schmidt & Miedaner, 2012)

Figure 39 illustrates investment costs of different TES methods located in Denmark and Germany. All investment cost are scaled to water equivalent volumes for fair comparison between different methods. Black quadrangle in Figure 39 illustrates the possible price range of SCC storage in water equivalent volume. Reason for BTES and ATES systems having much less price fluctuation between different storage sizes is that storage volume is obtained by drilling boreholes. When increasing storage volume of BTES the number of boreholes is also increased. Drilling costs of one meter of borehole remains constant and for this reason prices stay in same range regarding the storage size. Typical drilling cost according to InnoAir (2015) is 35 € per meter, but the drilling cost is almost double when drilling into soil. For this reason thin soil layers are usually removed before the drilling process.

Storages that use water reservoir as tank for storage media storage volume addition is gained by expanding the reservoir volume. Excavations do not have constant unit cost. Unit cost for excavating decreases when the volume of excavation increases. This effect is illustrated in Figure 39 and applies both pit and cavern storages.

Zinko and Gebremedhin (2009) created an equation for defining excavation cost of a CTES system of different volumes, with the Lyckebo storage as benchmark. Converting the 1983 price to match price of today by using Construction Price Index, this price came up to 41.46 €m^{-3}. The equation is following:

$$C_{storage} = C_{reference} * (\frac{V}{V_0})\char94 0.3 \tag{7}$$

Where $C_{storage}$ = Cost of the storage [€ m^{-3}]
$C_{reference}$ = Cost of the reference storage [€ m^{-3}]
V = Volume of the storage [m^3]
V_0 = Volume of the reference storage [m^3]

By plugging the 14600 m^3 volume of the SCC into the equation the price per cubic meter gets to 75 € level. This number illustrates the effect of unit costs decreasing as the volume increases.

Table 11: Costs of different storages

Location	Built [year]	Storgage type	Storage volume [m^3]	Cost [€]	Cost per m^3 [€ m^{-3}]
Munich	2007	TTES	5700	953 000	167.19
Eggenstein	2007	PTES	4500	433 000	96.22
Crailsheim	2008	BTES	37500	520 000	13.87
Rostock	2000	ATES	20000	171 000	8.55
Uppsala	1982	CTES	104300	4 324 000	41.46

Table 11 illustrates costs of different storage types. The lack of small scale CTES systems is the reason for choosing the Lyckebo storage located in Uppsala. All other storages are from the small side of TES projects.

Site requirements

Resources use depends on the final location where the SCC is built, but different TES methods require greatly varying ground conditions. Following listing will illustrate different method specific requirements:

The site requirements for ATES system are following. Aquifer of porous material that enables high hydraulic conductivity to ensure necessary yield of water. Schmidt and Mielander (2012) suggested that the hydraulic conductivity would have value above 10^{-5} m s^{-1}. Ground water flow should not be substantial to prevent heat losses. According to Lee

(2013) groundwater flow below 0.11 m day^{-1} is favored when choosing site for large scale aquifer with hourly yield of over 500 m^3.

The site requirements for BTES system are following. Shallow soil layer on top of the bedrock when drilling the storage into hard rock. Nordell (1994) reported that BTES storages in crystalline bedrock are only influenced by groundwater movement when conditions are extremely unfavorable. When BTES system is drilled into soil no substantial groundwater movement is allowed to prevent heat losses.

The site requirements for CTES system are following. Only shallow soil layer on top of the bedrock, but a bedrock outcrop is ideal for access tunnel. CTES requires stable bedrock and Finnish crystalline bedrock fulfils this demand. Intact rock is preferred. In Finland site investigations should concentrate on finding possible fault zones which might require heavy reinforcement and grouting work and avoid these locations.

The site requirements for PTES system are following. Groundwater level should be below the bottom of the pit as water conducts heat away from the storage as the lining is not insulated. Soil that is excavated from the pit should be able to be used for embankments around the pit to increase water reservoir volume.

The site requirements for TTES are following. Stable ground conditions to minimize the cost of groundwork for foundations. TTES can be built almost anywhere and it does not have any restrictions other than cost effectiveness.

Safety and environmental effects

SCC involves ordinary people as residents. For these people SCC should be invisible for the exception of the solar collectors on the roofs of the buildings. The risks involved with the seasonal storing should be non-existing for residents. Most of the storages are located underground and therefore they represent no risk for residents. PTES system without gravel filling is only storage method that has a risk for fatal accident that involves outsiders. The risk is that someone would get on top of the floating cover with a car or similar heavy object that would penetrate the floating cover and sink to the pit. This scenario is unlikely and can be minimized by making a barrier that surrounds the pit. The most realistic risk is involved with solar collectors and the piping that circulates the heat transferring fluid (HTF). Leakage in this piping system could cause burns if heated HTF got into contact with skin.

Environmental effects and risks have to be minimized while storing great amounts of energy. When the storage uses bedrock or groundwater as storage media environmental effects are caused. With BTES system the bedrock is heated up but this is affecting only the borehole field and limited area surrounding the borehole field as the escaping heat heats up the surrounding bedrock. Only if there are buildings that are built directly on the borehole field or immediacy of it this might heat up the cellars. ATES system that uses groundwater as storage media can have more severe effects. The groundwater chemistry can be altered when the groundwater is heated. This may cause pH changes and alternate bacterial composition in the groundwater. HTF that is circulating in closed systems should be non-toxic and environmentally safe. Reason for this is the risk of pipe breakage that would cause HTF to leak into the ground. All of the seasonal storing methods that use storage media that is or is in direct contact with ground should use water as HTF.

Surface area that is required by the storage can be re-used in most cases. Only the PTES system without gravel cannot have anything on top of it. A great option to be built on top of the BTES is park, a parking lot, a football field, or a greenhouse that is heated with escaping heat. With park on top of the system the possible maintenance that requires small excavations to get in touch with piping are easy to execute. This could happen, for example, if it is noticed that one of the piping strings is leaking. The parking lot option would gain benefit from the escaping heat as it would heat up the asphalt. This would keep the parking lot unfrozen for most of the year.

3.2.3 Sizing criteria

Sizing the storage correctly is a critical phase for the SCC project. Storage that does not meet the capacity demands of the SCC project compromises the whole project. The most optimal sizing implements the capacity requirement in most cost efficient way. This optimization can be done by choosing correct shape for the storage. Storages that use water as storage media need correct aspect ratio for thermal stratification. CTES systems need additional study on rock mechanical stability as the most optimal aspect ratio for thermal stratification might be unstable. Optimizing of the surface to volume ratio is also important as the heat losses occur from the outer sides of the storage. This optimization can be done with computer software that simulates the physics involved with thermal energy storage. For accurate results site specific input values must be used for these simulations. With these simulations the amount of heat losses can be estimated beforehand.

3.2.4 Storage duration

According to preliminary design SCC project will have two short term thermal storages (STTS) which are used for domestic hot water (DHW), space heating (SPH), and as buffer storage for the solar collectors. Reason for two STTSs is that the DHW requires constant water temperatures above 60 °C to prevent bacteria grow in the water tank and the SPH can be managed with lower temperatures. Solar collectors are connected to the DHW tank and when the temperatures rise above certain temperature level surplus heat is directed to SPH tank and when that energy is not needed for space heating it is directed to the seasonal storage. The buffer storage is also needed for efficient charging of the seasonal storage at steady pace where there are no high fluctuations for heat transferring fluid temperatures. Buffer is also important when discharging the seasonal storage as the slow discharging rates may be insufficient during the most intense peaks in heating energy demand. STTS will be charged on a constant pace during all hours of discharging of the seasonal storage.

Short term thermal energy storing requires storage media that has good thermal conductivity for quick response to demand of energy. Water fulfils this criteria and storages that use water as storage media are suitable for short term storing.

4 Selection of the method

4.1 Choosing the location for the SCC project

When deciding the optimal location for the solar community concept (SCC) village southern Finland has one major advantage. The average temperature is highest when comparing to other areas of Finland. This means below average amount of heating degree days which decreases the annual heating energy demand. This decreases the demand of stored energy. As the required storage capacity decreases the required storage volume decreases as well. As the time when the thermal energy storage is charged remains to be the summer months the charging power can be reduced. This reduction can be done by decreasing the solar collector area. Both of these size reductions lead to cost savings which can have major effect on the economic feasibility of the SCC project.

As the SCC project is in a phase where the location of the village is not known the recommendations are general guidelines that must be reevaluated when the location is chosen. The location can be chosen so that the storage method is predetermined and location is chosen be most suitable for that method, or the location is predetermined and system is chosen to be most suitable for that location. If the location is chosen first then the site investigations must be done. These investigations must include finding out if there is movement in the ground water, how thick layer of soil there is on top of the bedrock, if there is an aquifer, and if there is some abandoned caverns that could be used for seasonal storing.

4.2 Choosing the seasonal thermal energy storage for SCC

Table 12 was used for the final decision when choosing the best seasonal storage for SCC project. This simple table summarizes the most important factors that must be taken into consideration when choosing a seasonal storage. Each category is scored from one to three "+" signs, three being the best score.

Table 12: Evaluation of different storage systems

	ATES	BTES	CTES	PTES	GWPTES	TTES
How easily required storage volume is obtained:	+++	+++	++	++	++	++
Cost efficiency of a small scale system:	+++	++	+	+	+	+
Storage efficiency:	++	+	+++	++	++	++
How site specific the method is:	+	++	++	++	++	+++
Adaptability:	+++	+++	+	+	+	+
Small scale feasibility:	+++	+++	+	+	+	+++
Simplicity of the storage system:	+++	+++	++	+	++	+

Criteria of how easily required storage volume is obtained measures the simplicity of the building phase of the storage. ATES and BTES gets better score than other solutions because drilling of the boreholes is simpler than building a reservoir for water. Cost efficiency of a small scale measures the amount of initial costs that are involved with different TES systems. CTES, PTES, GWPTES are methods that require large volumes to be economically feasible. TTES is always expensive solution and should be only used when other methods are not possible. ATES is the cheapest solution in small scale followed by BTES. Storage efficiency is measurement of how much of the charged energy can be discharged. CTES system is the most efficient and the BTES system has biggest heat losses. Measurement of storage methods being site specific means that how flexible the storage is when choosing site to SCC village. Adaptability measures the possible change in storage size due increasing energy demand. BTES and ATES systems can acquire more storage volume by adding boreholes or well pairings, but other methods cannot increase the storage volume this easily. Small scale feasibility tells the feasibility of different systems in small scale. Simplicity of the storage system measures the simplicity of the storage as whole taking into account all aspects from building phase to energy storing.

Recommendation for seasonal storage method for SCC project is borehole thermal energy storage (BTES). This method was chosen by eliminating unsuitable methods by reviewing SCC projects demands and how they limit storage options. Quick summary of storing needs for SCC project is a seasonal storage that fulfils annual heating energy demand of 306 MWh as cost effectively as possible.

The storage capacity combined with cost efficiency requirement defines CTES, PTES, and GWTES out as these methods require greater capacity requirements before unit costs are reduced to feasible levels. As the SCC is still in phase where the location of the village is not defined the storage method must be suitable for as many sites as possible. For this reason ATES is ruled out as it requires suitable aquifer. At this stage of the ruling out process only BTES and TTES are left. The reason for choosing BTES over TTES was simplicity of the storage, cost effectiveness, and favorable ground conditions in Finland. BTES system has also advantage in form of adaptability if there is increased demand for stored heating energy the existing storage could be modified by drilling additional boreholes around the borehole field. Only ATES system has similar simple solution for additional storage capacity. In conclusion BTES, was chosen because it is a storage method that is simple to build, cost effective, feasible in small scale, and suitable in Finnish ground conditions.

Choosing BTES as storage system for SCC opens up the possibility to combine the seasonal storage and short term storage in same way as at Attenkirchen. Placing the short term storage middle of the borehole field without massive insulation might be cost effective solution. This idea has to be studied further and it is just an optional addition to SCC BTES system.

4.2.1 How changing the SCC village size affects the recommendation

SCC village is planned to have 50 houses and the choosing process of the seasonal storing method became moderately straight forward process as all the storages that needed great capacity were ruled out. This choosing process could be greatly different if the village size was increased.

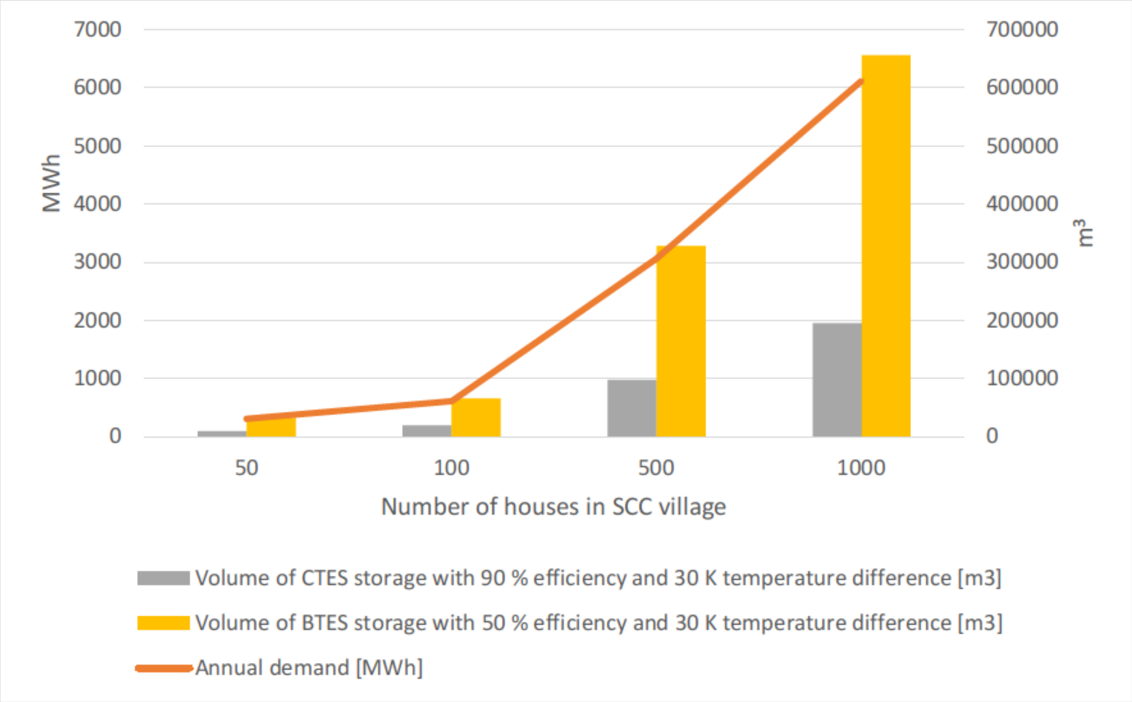


Figure 40: How increasing number of houses in SCC village affects storage volume requirements

Figure 40 illustrates how the energy demand of the SCC village increases when the amount of houses increase. In this example BTES and CTES systems are compared. BTES system has 50 % efficiency with 30 K temperature change and CTES system has 90 % efficiency with temperature change of 30 K. When the amount of houses increases by tenfold, systems that require great amounts to be economically feasible become available. Village with 500 houses utilizing a CTES system would require roughly 100 000 m^3 of storage volume. As the size of the village increases seasonal storing methods that require large scale to be feasible become valid options that needs to be taken into consideration.

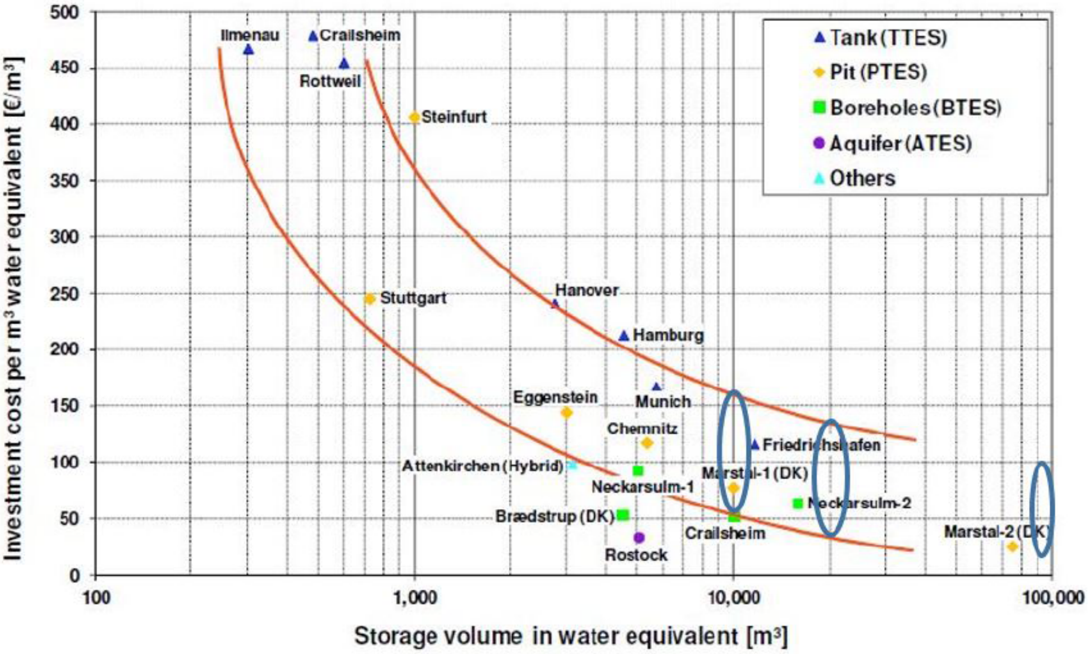


Figure 41: Illustration of what price range the seasonal storage of SCC would hit if size of the village was increased. Ellipsoid in the left represents the SCC village with 50 houses, middle ellipsoid is 100 houses, and the ellipsoid in the right side represents 500 houses. After (Schmidt & Miedaner, 2012)

Figure 41 illustrates how increasing the storage size decreases the price of one cubic meter of water equivalent storage media. In a storage method such as PTES, where obtaining of the storage volume is not the highest expense increasing the size substantially lowers price of the storage. By using data from Figure 40 three ellipses are drawn on Figure 41 to present the possible price ranges for the storage if the storage volume grows. The right side ellipse represent the price range of village with 500 houses. When comparing it to left side ellipsoid which represents the SCC village of 50 houses the price difference is substantial.

In a large scale project solar collectors could be installed centralized into a field of solar collectors. This would make the maintenance easier and residents would not be interfered during maintenance. The seasonal storage and the centralized collector field could be built before the village because it would help with heat losses in early years as the storage would have an additional year of heating before the energy would be discharged.

4.3 Recommended configuration for the storage

Required volume

The annual heating energy demand of the SCC village is 306 MWh. This is the amount of energy that must be extracted from the storage. Energy that is required to heat domestic hot water during summer months is taken directly from solar collectors and short term storages (STTS) and it is excluded from the required energy from the seasonal storage. Borehole storage with 40 % efficiency and 20 K temperature fluctuation would need volume of 61446 m^3 to meet the demand of heating energy. Reason for this efficiency value instead of higher value is the generality of the concept. By assuming too optimistic efficiency value consequences might be catastrophic for the solar energy goals as the recommended storage would have insufficient capacity. This would cause a situation where that inadequate capacity must be provided by conventional methods. This would lead to lower solar fraction which measures the amount of heat that is provided by solar energy. Solar fraction is the measurement for success in SCC project.

Optimal shape of the storage

The goal with TES is to maximize their efficiency, and this is done by minimizing heat losses. Heat losses are minimized by maximizing the volume-to-surface ratio. This is done by choosing cylindrical shape for the storage. Diameter of that cylinder should be the same as the depth of the boreholes. To obtain storage volume of 61446 m^3 optimally with cylinder shaped borehole storage the radius of the circle would be 21.4 m and the depth of the boreholes would be 42.8 m.

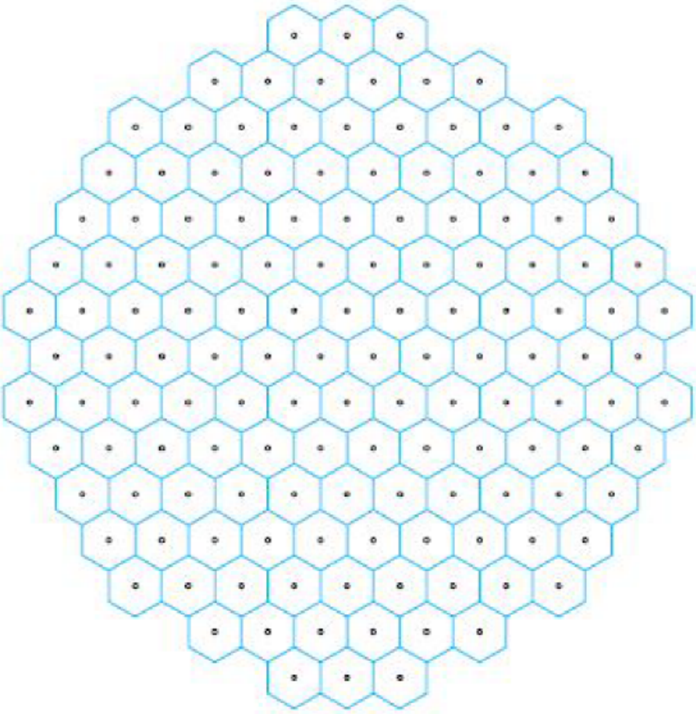


Figure 42: Recommended borehole configuration for SCC project contains 140 boreholes in hexagonal pattern. The name hexagonal pattern comes from the hexagonal area that each borehole gets when it is surrounded by other boreholes.

Recommended spacing between boreholes is 3.5 m in a hexagonal pattern that can be seen in Figure 42. The Final spacing between boreholes must be re-evaluated when the final location of the SCC village is chosen and thermal response tests are done. Borehole diameter is suggested to be 150 mm. Hexagonal pattern is chosen because it covers greater area per borehole with same spacing than square pattern. This configuration for SCC led to a borehole field of 140 boreholes. With borehole depth of 42.8 meters this equals as 5992 drill meters. Borehole field must be covered with insulation layer, suggested insulation is expanded polystyrene (EPS). Final thickness of insulation layer is calculated when the site is chosen.

Cost estimate

Schmidt and Mielander (2012) have estimated a typical BTES system cost to be in range of 50 – 80 € per borehole meter. This number includes heat exchangers, drilling and groundwork. Total drilling depth is 5992m. By applying the price range given by Schmidt and Mielander the cost of the BTES system in the SCC village is ranged between 0.3 M€

– 0.48 M€ €. This cost estimate only includes the BTES system and it does not include solar collectors, pumps and piping to houses.

5 Conclusions

When storing solar energy seasonally to provide heating energy to a village during cold months the amount of energy that is required to store is massive. Although phase change materials (PCM) and thermochemical reactions have advantage in storage capacity and storage efficiency the vast amount stored energy requires storage method that can acquire this massive storage capacity with easily obtainable and inexpensive storage media. These storage media requirements are easily filled by water, bedrock, and soil. At least one of them can be found anywhere and there is usually at least one seasonal storing method available for any location.

Location and size of the storage are key factors when choosing correct method for seasonal thermal energy storing. Cavern thermal energy storage (CTES) and pit thermal energy storage (PTES) become economically feasible only in large scale projects as they have expenses that need massive storage volume to overcome those costs. Tank thermal energy storage (TTES) is suitable for small scale projects with disadvantageous ground conditions as they are usually built on their own foundation above ground water level. Aquifer thermal energy storage (ATES) and borehole thermal energy storage (BTES) are suitable for both small scale projects and large scale projects. Site specific requirements of different TES methods needs to be taken into account when choosing suitable method for a specific location. Some locations may offer advantageous opportunities for some storing method that can save in building costs. For example a rock cavern that can be modified into a CTES system can save a lot of money.

Finnish environment is well suited for collecting solar heat during summer months and Finnish ground conditions are well suited for storing that heat seasonally. Insolation levels in Finland increase substantially during summer months to feasible levels for solar collectors. Stable crystalline hard rock is suitable for both small scale BTES and large scale CTES. Capacity requirement of SCC storage is on the small scale side and increasing the village size from 50 houses to 500 houses would have effect on the amount of feasible storage possibilities as unit cost of storage volume decreases substantially when the volume of the storage increases.

Recommended storage configuration for SCC project is a BTES system with total volume of 62 000 m^3. Boreholes are drilled into hexagonal pattern which is the most cost effective borehole pattern as it decreases the amount of drill meters.

6 Recommendations for future work

This literature study focused on thermal energy storing of solar energy for small residential area, but in the field of thermal energy storing there is great deal of topics for further research.

Research of possible advantages of massively upgrading the number of houses that would get their heating energy from one large scale thermal energy storage. This large scale storage could provide heating energy to a whole neighborhood or small town. These large scale storages could be connected to solar collectors and sources of industrial waste heat. This would minimize heat losses and construction costs when compared to solution where each residential area has its own small scale seasonal storage.

Further research with combining storage types could also be more beneficial in large scale as the economic advantages of combining different storage mediums would overcome initial costs more easily. This could be done by numerical modeling of different possible storage combinations. Surveying for empty caverns that could be modified more cost effectively into combi storage.

7 References

Alanen, R., Koljonen, T., Hukari, S., Saari, P., 2003. Energian varastoinnin nykytila, Espoo: VTT.

Barnes, F. S. Begeal, C. Decker, T., 2011. Large Energy Storage Systems Handbook. 1st ed. Boca Raton: Taylor & Francis Group.

Cabeza, L. Martonell, I., Miró, L., Fernández, A.I., Barreneche, C., 2015. Introduction to thermal energy storage (TES) systems. In: L. F. Cabeza, ed. Advances in Thermal Energy Storage Systems. Barcelona: Elsevier, pp. 1-28.

Converse, A., 2012. Seasonal Energy Storage in a Renewable Energy System. Proceedings of the IEEE, 100(2), pp. 401-409.

Dannemand, A. J., Bodker, L., 2013. Large Thermal Energy Storage at Marstal District Heating. Paris, Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering.

Dincer, I., Rosen, M., 2010. Thermal Energy Storage: Systems and Applications. 2nd ed. s.l.:John Wiley & Sons.

Drake Landing Solar Community, 2015. Drake Landing Solar Community. [Online]
Available at: http://www.dlsc.ca/
[Accessed 11 September 2015].

GTK, 2005. Pohjaveden synty ja esiintyminen. [Online]
Available at: http://weppi.gtk.fi/aineistot/mp-opas/pohjav_esiintyminen.htm
[Accessed 22 October 2015].

GTK, 2005. Suomen maaperän synty. [Online]
Available at: http://weppi.gtk.fi/aineistot/mp-opas/maapera.htm
[Accessed 26 November 2015].

Hauer, A., 2013. International Renevable Energy Agency IRENA. [Online]
Available at: www.irena.org/publications
[Accessed 8 August 2015].

Hellström, G., 2011. ICAX Interseasonal Heat Transfer. [Online]
Available at: http://www.icax.co.uk/pdf/REHAU_Hellstrom_UTES.pdf
[Accessed 7 September 2015].

Hellström, G., Larson, S., 2001. Seasonal thermal energy storage – the HYDROCK concept. Bulletin of Engineering Geology and the Environment, 60(2), pp. 145 - 156.

Hirvonen, J., Mohan, G., 2015. Preliminary sizing of a seasonal thermal storage

http://www.dlsc.ca/ Drake Landing Solar Community. [Online]
Available at: http://www.dlsc.ca/
[Accessed 17 4 2015].

Huang, P. M., Li, Y., Summer, M. E., 2012. Handbook of Soil Sciences properties and Processes. 2nd ed. Boca Raton, FL: CRC Press.

Ilmatieteen Laitos, 2014. Ilmatieteen laitos vuositilastot. [Online]
Available at: http://ilmatieteenlaitos.fi/vuositilastot
[Accessed 30 September 30].

Ilmatieteen Laitos, 2015. Ilmatieteen Laitos Heating Degree Days. [Online]
Available at: http://en.ilmatieteenlaitos.fi/heating-degree-days
[Accessed 30 September 2015].

InnoAir, 2015. Porakaivo / energiakaivo poraus - maalämpö. [Online]
Available at: http://www.innoair.fi/Porakaivo-poraus-maalampo-metrihinta
[Accessed 26 November 2015].

Jensen, M. V., 2014. Task 45 Large Systems: Seasonal pit heat storages - Guidelines for materials & construction. [Online]
Available at: http://task45.iea-shc.org/fact-sheets
[Accessed 18 August 2015].

Kauppa ja teollisuusministreriö, 1986. Keravan aurinkokylän energian käytön tutkimus 1986 - 1985, Helsinki: TKK.

Kukkonen, I. Lindberg, A., 1998. Thermal properties of rocks at the investigation sites: measured and calculated thermal conductivity, specific heat capacity and thermal diffusivity, Helsinki: Posiva Oy.

Kukkonen, I. Peltoniemi, S., 1998. Relationships between Thermal and other Petrofysical Properties of Rocks in Finland. Phys. Chem. Earth, 23(3), pp. 341-349.

Kuravi, S. Trahan, J., Goswami, Y., Rahman, M., Stefanakos, E., 2012. Thermal energy storage for concentrating solar power plants. Technology and Innovation, 14(2), pp. 81-91.

Lee, K. S., 2013. Underground Thermal Energy Storage. Seoul: Springer London.
Leidos Canada, 2014. Drake Landing Solar Community. [Online]
Available at: http://www.dlsc.ca/reports.htm
[Accessed 26 August 2015].

Lozano, M. A., Serra, L. M., Guadalfajara, M., 2014. Analysis of Large Thermal Energy Storage for Solar District Heating. At Lleida, Eurotherm Seminar #99.

Lund, P., Mäkinen, R., 1982. Keravan Aurinkokylä. 1st ed. Helsinki: Suomen Itsenäisyyden Juhlavuoden 1967 Rahasto, SITRA.

McClenahan, D. Gusdorf, J., Kokko, J., Thorton, J., Wong, B., 2006. Okotoks: Seasonal Storage of Solar Energy for Space Heat in a New Community

McDowell, T. P., Thorton, J. W., 2008. Simulation and model calibration of a large-scale solar seasonal storage system. Berkley, California, pp. 174 - 181.

NASA, 2015. NASA Surface meteorology and Solar Energy. [Online]
Available at: https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi?email=skip@larc.nasa.gov
[Accessed 29 9 2015].

Natural Resources Canada, [Online]
Available at: http://pv.nrcan.gc.ca/index.php?n=570&m=u&lang=e
[Accessed 20 4 2015].

Nielsen, K., 2003. Thermal Energy Storage A State-Of-The-Art, Trondheim: Department of Geology and Mineral Resources Engineering NTNU.

Nordell, B., 1994. Borehole heat store optimization, Luleå: Luleå University of Technology.

Nordell, B., 2000. Large-scale Thermal Energy Storage, Luleå

Nordell, B., Grein, M., Kharseh, M., 2007. Large-scale Utilisation of Renewable Energy Requires Energy Storage. Algeria, Université Abou Bakr BELKAID – TLEMCEN.

Nordell, B., Hellström, G., 2000. High temperature solar heated seasonal storage system for low temperature heating of buildings. Solar energy, 69(6), pp. 511-523.

Nordell, B., Ritola, J., Sipilä, K., Björn, S., 1994. The combi heat store - a combined rock cavern/borehole heat store. Tunnelling and Underground Space Technology, 9(2), pp. 243-249.

Nordell, B., Snijders, A., Stiles, L., 2015. The use of aquifers as thermal energy storage (TES) systems. In: Advances in Thermal Energy Storage Systems Elsevier Ltd., pp. 87-115.

Novo, A. V., Bayon, J. R., Castro-Fresno, D., Rodriquez-Hernandez, J., 2010. Review of seasonal heat storage in large basins: Water tanks and gravel–water pits. Applied Energy, Volume 87, pp. 390-397.

Nuβbricker-Lux, J., Bauer, D., Marx, R., Heidmann, W., Müller-Steinhagen, H., 2009. Monitoring results from German central heating plants with seasonal thermal energy storage. Stocholm, EFFSTOCK 2009.

Park, D., Park, E.-S., Sunwoo, C., 2014. Heat transfer and mechanical stability analyses to determine the aspect ratio of rock caverns for thermal energy storage. Solar Energy, Volume 107, pp. 171-181.

Pinel, P., Cruickshank, C. A., 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, Issue 15, pp. 3341-3359.

PlanEnergi, 2015. SUNSTORE 3 Phase 2 Implementation, Skorping: PlanEnergi.

Ramstad, R. K., 2004. Ground source energy in crystalline bedrock - increased energy extraction by using hydraulic fracturing in boreholes

Reuss, M., 2015. The use of borehole thermal energy storage (BTES) systems. In: L. F. Cabeza, ed. Advances in Thermal Energy Storage Systems. 1st ed. Bayern: Woodhead Publishing, pp. 117-147.

Reuss, M., Beuth, W., Schmidt, M., Schoelkopf, W., 2006. Solar District Heating With Seasonal Storage in Attenkirchen. Stockton, ECOSTOCK. 10th International Conference on Thermal Energy Storage.

Rezaie, B., Reddy, B. V., Rosen, M. A., 2014. Energy analysis of thermal energy storage in a district energy application. Renewable Energy, Issue 74, pp. 848-854.

Ritola, J., 1990. Oulun kalliolämpövarasto, Espoo: VTT Offsetpaino.

Schmidt, T., Kabus, F., Müller-Steinhagen, H., 2000. The Central Solar Heating Plant with Aquifer Thermal Energy Store in Rostock, Germany. Stuttgart

Schmidt, T., Mangold, D., 2006. New Steps in Seasonal Thermal Energy Storage in Germany, s.l.: Solites - Steinbeis Research Institute for Solar and Sustainable Thermal Energy Systems.

Schmidt, T., Mangold, D., Müller-Steinhagen, H., 2004. Central solar heating plants with seasonal storage in Germany. Solar Energy, 76(1-3), pp. 165-174.

Schmidt, T., Mangold, D., Sorensen, P. A. N. F., 2011. Large-scale heat storage, Berlin: PlanEnergi.

Schmidt, T., Miedaner, O., 2012. Solar District Heating. [Online]
Available at: www.solar-district-heating.eu
[Accessed June 2015].

Schmidt, T., Müller-Steinhagen, H., 2004. The Central Solar Heating Plant with Aquifer Thermal Energy Store in Rostock - results after four years of operation. Freiburg

Sibbit, B., McCleanhan, D., 2014. Tas 45 Large systems. [Online]
Available at: http://task45.iea-shc.org/fact-sheets
[Accessed 9 September 2015].

Sibbitt, B. McClenahan, D., Djebbar,R., Thornton, J., Wong, B., Carriere, J., Kokko, J., 2011. The Performance of a High Solar Fraction Seasonal Storage District Heating System - Five Years of Operation. Energy Procedia.

Sipilä, K., 1989. Oulun kalliolämpövarasto: Osa 1 Lämpövaraston käyttö ja hankkeen kannattavuus, Espoo: VTT Offsetpaino.

Soininen, S., 2013. Ratojen routaongelmat Suomessa, Helsinki: Liikennevirasto.

Underground Energy, L., 2015. Underground Energy. [Online]
Available at: www.underground-energy.com
[Accessed 11 September 2015].

Wincott, N., 2011. Integrating Ground Source with other Energy Technologies, Cambridge: NeoEnergy (Sweden) Limited.

Worthington, M. A., 2014. District Energy. [Online]
Available at: http://www.districtenergy.org/assets/pdfs/2014-Campus-Atlanta/Track-B/5B.3Worthington.pdf
[Accessed 23 October 2015].

Yang, Z., Chen, H., Wang, L., Sheng, Y., Wang, Y., 2015. Comparative study of the influences of different water tank shapes on thermal energy storage capacity and thermal stratification. Renewable Energy, Volume 85, pp. 31-44.

Zinko, H., Gebremedhin, A., 2009. Seasonal Heat Storage in District Heating Systems. Linköping, Linköping University.

8 Appendix

8.1 Installation of the TES system

When TES is built the route from planning phase to the first test charging vary greatly between different methods. Following listings conclude the main phases for each considered TES method.

Aquifer thermal energy storage (ATES)

1. Site investigations for defining the hydro-geological parameters of the aquifer to be suitable for ATES. This includes defining, depth, thickness, hydraulic conductivity, transmissivity, hydraulic gradient, and porosity of the aquifer. Also velocity of the groundwater flow must be measured. (Worthington, 2014)
2. Running computer simulations for distance between hot wells and cold wells to prevent thermal short circuiting between wells. This short circuiting occurs when the hot water and cold water is mixed together. Short circuiting leads to lowered storage efficiency which leads to need of larger solar collector area. Larger collector area costs more and lowers the economic feasibility of the storage system.
3. Drilling desired amount of well pairings.
4. Installing piping system for both pumping and injecting into the wells.
5. Connecting the piping system into a heat exchanger.

Borehole thermal energy storage (BTES)

1. Site investigations must be done to be sure that there is no roughness zones on the chosen site that could have substantial groundwater flow. Thermal response tests on the site is required for most optimal spacing between boreholes. (Sibbit & McCleanhan, 2014)
2. When the size and depth of the borehole field is determined the height of soil layer above the bedrock is measured by drillings. If the soil layer is shallow it can be excavated away. If it is too thick to be excavated protecting casing is needed when drilling the boreholes.

3. Boreholes are drilled into a pre-designed formation in a way that amount of boreholes is minimized, but the storage volume is obtained in a way that the whole storage volume is utilized in full potential. Usually this leads to distances of 2 – 4 m between boreholes.
4. Heat exchangers are installed into boreholes.
    a. For closed system installed heat exchangers are U-pipes that circulate the heat transferring fluid.
    b. For open systems injection pipe is installed in a way that allows injecting hot water into bottom of the borehole. This water is collected at the top of the borehole.
5. Depending on site conditions and chosen system grouting may be used for better heat convection. Grouting is only needed when the groundwater flow through the BTES system is substantial and causing heat losses. Stationary groundwater does not cause problems as water has good thermal conductivity and it improves the heat conduction from U-piping to rock mass.
6. Each borehole is connected to another borehole. Boreholes are connected in a configuration that creates a string of boreholes that begins from middle of the borehole field and ends at the outer edge of the borehole field. This configuration maximizes the charging and discharging power of BTES system. There are multiple strings of boreholes in the borehole field.
7. Boreholes are connected to a central heat exchanger.

Cavern thermal energy storage (CTES)

1. Site investigations are required to obtain information about the rock types of the site, rock mechanical parameters, and rock stresses.
2. After the required storage volume is calculated the storage shape is chosen. It is important to choose the storage shape in a way that maximizes thermal stratification in the cavern but is still rock mechanically stable to be safe.
3. Excavating and reinforcing the cavern.
4. Grouting the cavern to be as watertight as possible. Any leakage to cavern or out from the cavern leads to heat losses which will lower the overall efficiency of

the storage. Lower efficiency leads to higher costs and may compromise the economic feasibility of the storage.

5. Installation of heat exchanger piping system.
6. Filling the cavern with water

Pit thermal energy storage (PTES)

1. Site investigation with drillings must be done to determine soil parameters for maximum slope inclination for the pit walls and if the soil is usable for building embankments around the pit to increase the volume cost effectively.
2. Excavation of the pit and moving the excess soil, that is not used in embankments, away
3. Installation of the central charging and discharging piping system.
4. Installation of watertight lining on bottom and walls of the pit. This phase has to be done with high precision. Every seam that has been welded must pass welding test to achieve 100 % watertight lining.
5. Depending on the chosen storage media:
   a. Pit is filled with water
   b. Pit is filled with water and gravel mixture
6. The pit is covered with an insulated lid
   a. If the pit is filled with water the cover has to be a floating cover. This floating cover has no structural strength to support any external loads.
   b. If the pit is filled with gravel and water mixture the gravel can support load and it is possible to build something light on top of the PTES.

Tank thermal energy storage (TTES)

1. Site investigations for finding out the required method for foundation reinforcements.
2. Proper groundwork to support the tank is needed.
3. Casting a foundation
4. Assemble pre-manufactured elements and piping system
5. Fill with water
6. Cover with soil for better insulation