Lappeenranta-Lahti University of Technology LUT

LUT School of Energy Systems

Energy Technology

Master's thesis

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Techno-economic analysis of seasonal thermal energy storages in public real estates

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Lappeenranta 29.04.2020

ABSTRACT

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Techno-economic analysis of seasonal thermal energy storages in public real estates

School of Energy Systems

Energy Technology

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Master's Thesis 2020

81 pages, 27 figures and 22 tables

Keywords: Seasonal thermal energy storages, public real estates, borehole thermal energy storage, aquifer thermal energy storage, pit thermal energy storage, tank thermal energy storage

The object of the study was to develop an Excel-model to evaluate and compare the economic potential of seasonal energy storages. The model is used for dimensioning four different storage options to store the additional heat demand required during the heating period, when circa 80 % of the annual heat demand is covered with a heat pump. The stored energy originates from extracted heat during cooling period and heat from ambient air produced by the heat pump.

The technical applicability of the storage systems was evaluated based on the geological and hydrological features. The study investigated the techno-economic potential of seasonal storage options for selected real estates. The Excel-model evaluates the investment costs and achieved annual savings for the case real estates, including the increase in electricity consumption. The storage investment costs, savings and payback periods were compared.

The study found a technically applicable storage type for seven out of 12 real estates, from which five out of seven were economically potential with a payback period less than 15 years. The specific costs were influenced the most by the applied storage type. The annual savings were influenced by the ratio between cooling and heating demand and by the efficiency of the storage. The study found that the heating and cooling demand, and the heating system requirements had a significant impact on the economic potential at the investigated real estates.

TIIVISTELMÄ

Julia Keskitalo

Kausilämpövarastojen teknis-taloudellinen tarkastelu julkisissa kiinteistöissä

School of Energy Systems

Energiatekniikan koulutusohjelma

Diplomityö 2020, LUT-yliopisto, 2020

Ohjaaja Mirika Knuutila

81 sivua, 27 kuvaa ja 22 taulukkoa

Avainsanat Kausilämpövarastot, julkiset kiinteistöt, porakaivolämpöenergiavarasto, pohjavesilämpövarasto, kuoppalämpövarasto, tankkilämpövarasto

Työn tavoitteena on tehdä Excel-työkalu lämmön kausivarastojen taloudellisen kannattavuuden arviointiin ja vertailuun. Työkalussa mitoitetaan neljä eri varastoratkaisua varastoimaan lämmityskauden lisälämmöntarve, kun noin 80 % vuotuisesta lämmöntarpeesta tuotetaan ilmalämpöpumpulla. Työkalussa varastoitava energia on peräisin jäähdytyksessä poistetusta lämmöstä ja lämpöpumpulla ulkoilmasta tuotetusta lämmöstä.

Varastoratkaisujen tekninen soveltuvuus arvioitiin kiinteistökohtaisesti geologisten ja hydrologisten ominaisuuksien perusteella. Työssä selvitettiin teknisesti ja taloudellisesti sovellettavissa olevat kausivarastoratkaisut. Työkalu arvioi sovellettaville varastoille investointikustannukset ja vuotuiset säästöt lisääntynyt sähköntarve huomioiden. Varastoja vertailtiin investointikustannusten, säästöjen ja yksinkertaisten takaisinmaksuaikojen avulla.

Työssä löydettiin teknisesti sovellettavissa oleva varastotyyppi seitsemään 12 kiinteistöstä, joista viisi seitsemästä olivat taloudellisesti kannattavia alle 15 vuoden yksinkertaisella takaisinmaksuajalla. Ominaisinvestointikustannuksiin vaikutti eniten sovellettava varastotyyppi. Vuotuisiin säästöihin vaikuttivat jäähdytystarpeen määrä suhteessa lämmitystarpeeseen, sekä varaston hyötysuhde. Tutkimus osoitti, että kiinteistön lämmitys- ja jäähdytysenergiantarve, sekä lämmitysjärjestelmän vaatimukset vaikuttivat merkittävästi investoinnin taloudelliseen kannattavuuteen tarkasteltavissa kiinteistöissä.

FOREWORD

“The perfect is the enemy of the good.”

-Voltaire

This Master’s thesis is made at LUT-University with data collected and simulated in *Public-Private Partnership in real estate energy efficiency improvements and finance* –project. The purpose of this research was to discover the economic potential of thermal energy storages in project’s case real estates.

I would like to thank Petteri Laaksonen and Mirika Knuutila for offering me the chance to work in the project and to write my Master’s thesis on a topic I found specially interesting. Thank Petteri Laaksonen also for sharing a quote during a project meeting, which became my work mantra during the study. I want to thank Ahti Jaatinen-Värri for advising me and helping me to improve my work. Special thanks go to Mirika Knuutila for supervising and supporting me during the process but especially for answering to all the questions I came across.

I would also like to thank my colleagues for providing peer support and inspiration during coffee breaks, specially Miika Lönnblad for his support in heat pump calculations and thermodynamic matters.

Last but not the least, I want to thank my family and friends from support during my studies and at the start of my career. Especially the one at home.

Lappeenranta 28.04.2020

Julia Keskitalo

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SYMBOLS AND ABBREVIATIONS

Latin symbols

A	area	m^2
C	heat capacity	kJ/(kgK)
C	constant	$W/(m^3kg)$
c_p	specific heat capacity	kJ/(kgK)
c_v	volumetric heat capacity	$kWh/(m^3K)$
d	day	
dh	enthalpy change	kJ/kg
f	frequency	Hz
g	gravity	m/s^2
h	hour	
h	depth	m
L	screen length	m
m	mass	kg
m	month	
n	porosity	
n	number	
P	power	kW
Q	heat energy	kWh
q_v	volumetric flow	m^3/s
R_{th}	thermal radius	m
T	temperature	K/°C
t	time	
U	thermal transmittance	$kW/(m^2K)$
V	volume	m^3

Greek symbols

Δ	difference	
η	efficiency	%
η_t	time of use	
λ	thermal conductivity	W/(mK)
ρ	density	kg/m^3

Dimensionless parameters

f	volumetric share
x	relative share

Subscripts

a	air
aq	aquifer
b	borehole
c	cooling
e	electricity
g	ground material
h	heating
hp	heat pump
i	indice
m	soil material
max	maximum
p	pressure
s	soil
s	storage
s	suction

v	volume
w	water

Abbreviations

ATES	Aquifer thermal energy storage
A/V	Area to volume
AWHP	Air-to-water heat pump
BTES	Borehole thermal energy storage
COP	Coefficient of performance
CTES	Cavern thermal energy storage
DHW	Domestic hot water
ERDF	European Regional Development Fund
EU	European Union
GSHP	Ground source heat pump
LHS	Latent heat storage
PCM	Phase changing material
PTES	Pit thermal energy storage
SHS	Sensible heat storage
SeTES	Seasonal thermal energy storage
TCES	Thermochemical energy storage
TES	Thermal energy storage
TTES	Tank thermal energy storage
UTES	Underground thermal energy storage
VAT	Value added tax
ZEB	Zero emission building

1 INTRODUCTION

European Union (EU) has committed to develop a sustainable, competitive, secure and carbon free energy system by 2050. 36 % of the CO_2-emissions in Europe originate from the building stock and 50 % from the primary energy consumption is used in buildings, where 80 % of the energy is consumed for heating and cooling. To reach the carbon neutrality goals, the EU Member States and investors need to prioritize energy efficiency improvements in the renovation of the building stock. The EU directive on the energy performance of buildings and energy efficiency highlights the importance of ensuring, that taken measures aiming to reduce energy demand of a building include all relevant elements and technical systems. (2018/844/EU, 75–77)

In Finland, energy demand for space heating is high due to the northern location. In 2016 the space heating sector had a 27 % share of the total energy consumption in Finland (Statistics Finland 2017). The heating demand is typically low in summer, when heat from ambient air, sun and surface water is available, and high in winter, when heat is produced from combustion processes. Seasonal energy storages allow to use the heat energy available in summer during high demand in winter. Thermal energy storage (TES) applications enable more effective use of thermal energy inside the system boundaries and can increase the energy independency of buildings and increase the use of renewable energy.

Lappeenranta and Imatra are cities located in South-Eastern Finland in South Karelia. Both cities are a part of the Towards Carbon Neural Municipalities (Hinku) network and South Karelia has become the first regions to achieve the Hinku region position with minimum of 80 % of its inhabitants living in Hinku-municipalities. The city of Lappeenranta has 72 699 inhabitants and total area 1 756 km^2. Imatra has 26 525 inhabitants and total land area 191.3 km^2. The municipalities situate on the shore of the lake Saimaa and share border with Russia. The City of Lappeenranta aims to reach 100 % emission reduction from the 1990 level by 2050 and the City of Imatra aims to reach carbon neutrality by 2030. (Imatra 2019; Imatra n.d. a; Lappeenranta n.d. a–b)

Public real estates have high heat demand, which has significant impact in their yearly operation costs and greenhouse gas emissions. Heating covers 64 % from yearly energy demand in the studied case real estates in Lappeenranta and 58 % in Imatra, and causes all or nearly all CO_2 emissions created, since both municipalities purchase electricity only from renewable resources. The emissions can be further reduced by increasing the share of total electricity in energy demand and by reducing total consumption of energy.

Thermal energy storage applications can reduce the heat demand of the real estates, when heat from available sources, such as cooling or ambient air, is utilized for heating. TES can also improve the finance of real estates by reducing purchased energy and increasing energy independency. For municipality and national interests, TES applications offer energy efficiency improvements, more sustainable and more self-sufficient use of energy. When the share of renewable energy grows and the share of electricity in total energy production increases, TES systems can work as a buffer during peaks in energy production.

Presently, TES technology is not commonly applied in Finland and most of the existing and reported storage systems are cavern storages as a part of district heating system. Therefore, the study is mainly based on the information found in simulated or existing pilot plants in Europe, which may differ from Finnish conditions. Borehole and aquifer thermal energy storages are more commonly studied and applied in Sweden, where geological conditions are similar to Finland and calculations methods and studies can be applied more reliably to local conditions in Lappeenranta and Imatra.

The study is based on the research made in *Public-Private Partnership in real estate energy efficiency improvements and finance* –project. The project is executed in collaboration between Lappeenranta-Lahti University of Technology LUT, LAB University of Applied Sciences and local entrepreneurs. The project has received funding from the European Regional Development Fund (ERDF) and it includes five real estates from Lappeenranta and eight real estates from Imatra, which will be renovated in the near future. The energy efficiency improvements are planned to be carried out within the renovation to reach the best cost-efficiency. The purpose of the project is to find the most attractive energy efficiency investments and present the financial potential of the recommend actions.

This study concentrates on analysing economic and technological feasibility of seasonal storage applications for selected case real estates. An Excel-tool is developed for comparing chosen applications in techno-economic perspective in order to find out the economic potential of the investigated storage types. Chosen technologies are Tank Thermal Energy Storage (TTES) and Underground Thermal Energy Storage (UTES) systems, due to reasonable investment costs and maturity of the technology.

The data for the study is obtained from data material collected and simulated in the *Public-Private Partnership in real estate energy efficiency improvements and finance* –project and from the Excel-tool developed for comparing energy efficiency improvements and profitability by Mirika Knuutila (2019). The data is used as input values for the Excel-tool developed in this study. Basic knowledge of chosen technologies and their features, limitations, advantages and disadvantages are discussed in the following parts.

Information on the geological and hydrological conditions at the case real estates are collected from available public sources, which describe the general conditions at the area. The reported soil depth before bedrock is reported in one of three categories, < 10 m ; 10–50 m ; > 50 m, which is an uncertainty factor, especially in drilling calculations and investment costs. The hydrogeological information of the Vuoksenniska aquifer is based on the reported information from the observation wells at the nearby paper mill and applied according to the information on the surface height at the case real estate and the paper mill.

2 SUITABLE TECHNOLOGIES

The mismatch between the energy supply and demand brings out the need for sustainable storage options for balancing the temporal difference. Heat energy from sun, water and air are available during warm season in summer, whereas the demand for heat energy in buildings is high during the cold season. The mismatch between the heating demand and available renewable heat energy requests long-term storage options for seasonal storage of thermal energy (Figure 1).

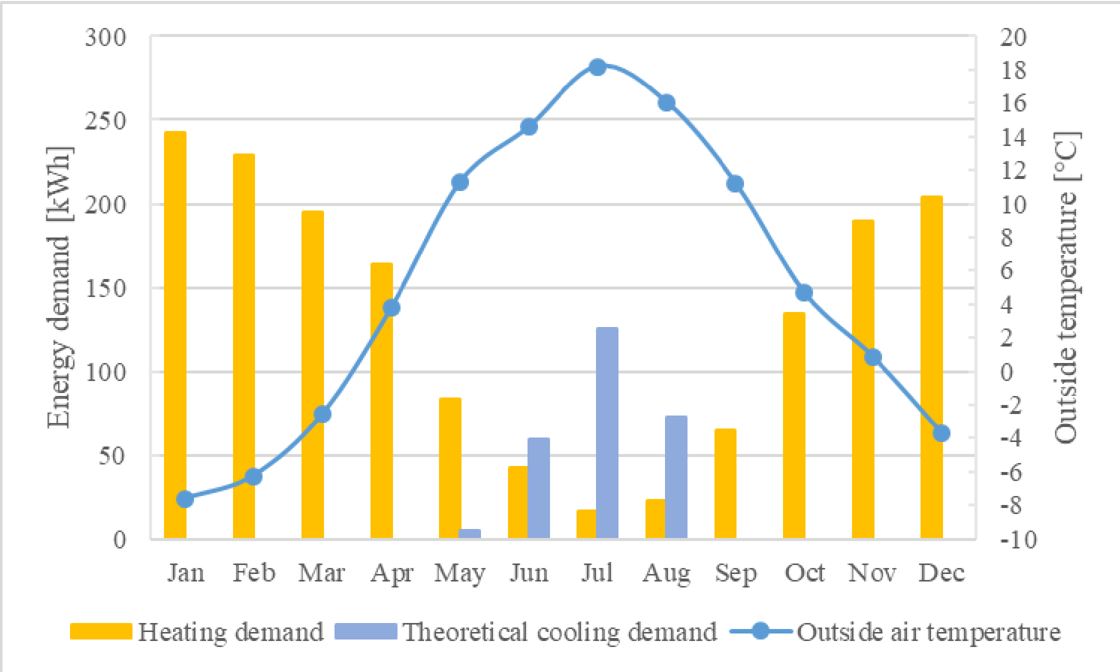


Figure 1. Heating and theoretical cooling demand in Lappeenranta City Hall. Data: *Public-Private Partnership in real estate energy efficiency improvements and finance* –project.

As seen in Figure 1, the heating demand is in its highest, when the outside air is in its coldest. Utilizing the air as heat source in cold temperature requires great amount of electricity and affects the heat pump performance. Also, the cooling demand is highest when the ambient air temperature is warmest and cold needs to be produced with electricity. To reserve and discharge great amounts of heating and cooling energy between seasons, the storage volumes need to be large (Nordell et al. 2007, 21.)

2.1 Thermal Energy Systems

TES systems can be divided by the form of stored energy in sensible heat storages, latent heat storages and thermochemical heat storages. Sensible heat storages (*SHS*) are based in temperature difference of the storage medium, which is either in gaseous, liquid or solid phase. Typical sensible storages are water-, rock- or ground based, such as hot water tanks or rock beds (Kalaiselvam 2014, 63). Material selection is based on its ability to store energy and on other important parameters of the material, such as density, specific heat capacity, thermal conductivity and diffusivity (Cabeza et al 2015, 3–4).

Latent heat storages (*LHS*) are based on the phase change of the storage material (*PCM*, *Phase Changing Material*), which absorbs or discharges energy. The storage medium is organic or inorganic material with high energy density and the phase change takes place typically between solid and liquid phase. Heat is stored in melting of the material and released during solidification. The disadvantages of LHS are the high cost of the storage material and the lack of thermal stability. (Cabeza et al 2015, 4–5; Kalaiselvam 2014, 63.)

New technology in energy storage systems is thermochemical energy storage (*TCES*) technology, which is based on absorption or adsorption of thermal energy or on chemical reactions releasing or absorbing heat energy. TCES materials have the highest energy density compared to other TES technologies but have low heat and mass transfer properties, especially in high densities. (Kalaiselvam & Parameshwaran 2014, 61–63.)

The specific costs of different TES technologies, efficiencies and storage durations are presented in Table 1.

Table 1. Comparison of TES technologies (IEA-ETSAP and IRENA 2013, 7).

TES System	Capacity (kWh/t)	Power (MW)	Efficiency (%)	Storage Period (hours, days, months)	Cost (€/kWh)
SHS	10–50	0.001–10	50–90	days/months	0.1–10
PCM	50–150	0.001–1	75–90	hours/months	10–50
TCES	120–250	0.01–1	75–100	hours/days	8–100

To balance the fluctuations in heat energy demand on a daily or monthly level, long-term thermal storages are the most efficient and effective solutions. Currently available seasonal thermal energy storage (*SeTES*) systems are sensible heat storages, which use water or solid material as storage medium. Sensible heat storages can store heat from hours to months and capture the surplus heat to later release. The most commonly applied seasonal energy storages are underground thermal energy storages (*UTES*), where heat and cold are stored in the subsurface.

2.2 Underground Thermal Energy Storage

The most applied TES systems are underground thermal energy storages, which store energy long-term in large-scale reservoirs. In UTES the ground, groundwater or energy piles are used as large heat exchangers between the heat source and the heat sink. Heat energy from sun, air and surface water can be charged in summer for discharging in winter, as well as storing cold energy from winter for cooling in summer. Typical operating modes in combined heating and cooling can be seen in Figure 2.

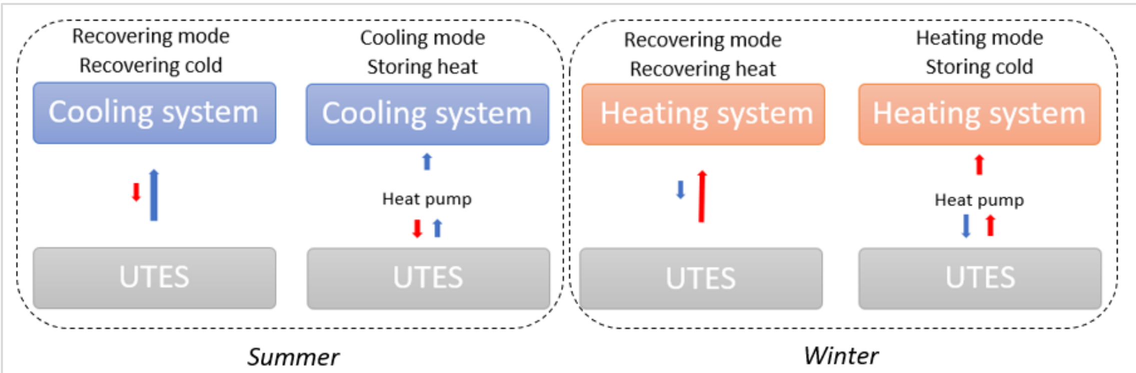


Figure 2. Operating modes of a combined heating and cooling system.

UTES systems can be either close or open loop systems. In a closed system the working fluid is pumped through a closed loop in the ground and in an open system the groundwater is pumped from the ground and injected back to the ground into wells or caverns. Most common UTES systems are borehole thermal energy storages (BTES), aquifer thermal energy storages (ATES), cavern thermal energy storages (CTES) and pit thermal energy storages (PTES). (Lee 2013, 15–20.)

Below 10–15 m surface, the ground temperature does not get influenced from outside temperature and stays warmer in winter and cooler in summer compared to the ambient air. In the depth of 10–20 m, also the groundwater temperature remains nearly constant and is 12 degrees higher than the annual mean outside air temperature. Below 20 m, the ground water temperature rises around one degree every 35 meters in depth. For that reason, the ground and groundwater are good storage materials for seasonal thermal storage options. Schematic picture from different UTES types is presented in Figure 3. (Nordell et al 2007, 21)

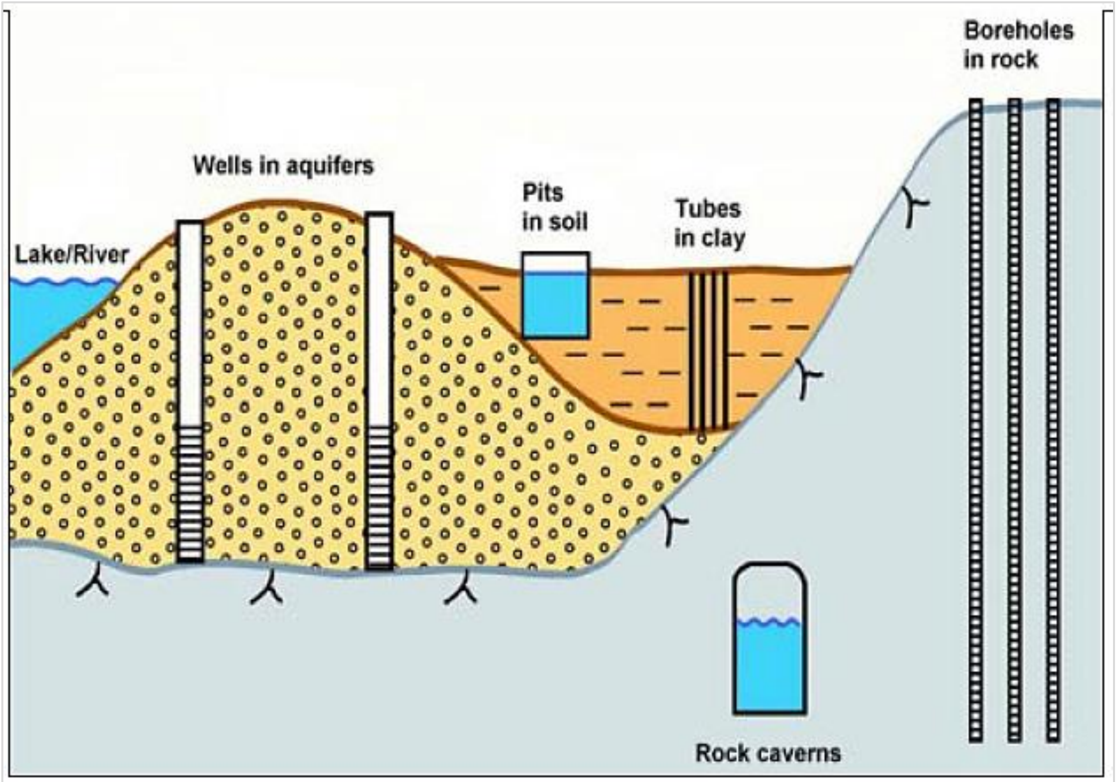


Figure 3. The most UTES types. (Nordell et al 2007, 21)

UTES systems work either in high or low temperature levels, depending from the storage temperature. Low-temperature UTES operates in the storage temperature ranging from 0 to 40–50 °C and can be applied for cooling, combined heating and cooling and low-temperature heating. Low-temperature UTES is often combined with a heat pump to supply heat in higher temperature levels for space heating. On the other hand, high-temperature UTES works at temperatures above 40–50 °C up to 95 °C. The possible heat sources for charging the storage are solar collectors, ambient air and waste heat. Ground source heat pumps (GSHP) work with the same principle as borehole thermal energy storages, and large-scale applications can be seen as a type of UTES. (Lee 2013, 18–23; IEA DHC 2018, 15)

Depending from the application and purpose, the supply temperatures range from temperature below freezing point up to 15 °C, but operation temperatures are typically between 6–15 °C. ATES systems can operate in temperature range of 4–5 °C and BTES below the freezing point, but both operate in higher efficiencies between 8–10 °C. Some design temperatures of UTES systems in operation are listed in Table 2. (Lee 2013, 23–24.)

Table 2. Technical design data from central solar heating plants with seasonal storage systems in Germany. (Schmidt et al 2003, 4.)

	Friedrichshafen	Neckarsulm	Hannover	Steinfurt	Rostock
Start of operation	1996	1997/2001	2000	1998	2000
Storage type	TTES	BTES	TTES	PTES	ATES
Heated net area, m^2	39 500	-	7 365	3 800	7 000
Heated storage volume, m^3	12 000	63 000	2 750	1 500	20 000
Total heat demand, MWh/a	4 106	3 960	694	325	497
T_{supply}/T_{return}	70/40	60/40	70/40	50/25	50/30

In addition to savings in cooling and heating, the UTES systems are usually beneficial due to electricity saving from cooling systems. The electricity saving contributes to positive environmental impact, when electricity production of emission causing energy sources reduces. The storage systems can induce energy savings for several years during the long lifetime. The UTES systems are usually economically profitable, with a typical payback time less than five years. (Lee 2013, 25.)

Although it is practically possible to find a suitable UTES system for almost any location, different UTES types set different geological and hydrological requirements for the installation. Pit storage requires stable ground conditions and preferably no groundwater close to the surface, whereas existing groundwater is favourable in BTES and a necessity in ATES. BTES and ATES systems have also further requirements from the geological site, which requires more extensive pre-investigations. From UTES systems CTES is not further studied, because there are no available caverns at the case real estates and excavation of a new cavern is not economically favourable. (Lee 2013, 21–23.)

2.3 BTES

Borehole thermal energy storages use underground rock or ground as storage material. Even if sensible heat storages are expected to have high heat capacities, underground storages may have only half the volumetric thermal capacity of water. Therefore, the volumes of underground storages may be double the size of water in the same operating temperatures. Porousness and high groundwater content increase the heat capacity of the storage medium, but existing underground flow reduces the thermal capacity by transporting heat away from the storage via convection. (Reuss 2015, 117–118.)

In BTES the surrounding mass acts as insulation at the sides and at the bottom of the storage and only the top surface can be insulated. The conductivity of the ground material is typically between 1 and 5 W/(mK). To obtain reasonable efficiencies, the volume of the storage needs to be large to compensate the thermal losses from the storage to the surroundings. The storage area-to-volume (A/V) ratio should be optimized with minimal drilling to avoid the increase of investment cost. The relation between A/V ratio and volumetric heat losses is shown in Figure 4. (Mangold et al 2016, 21; Reuss 2015, 117.)

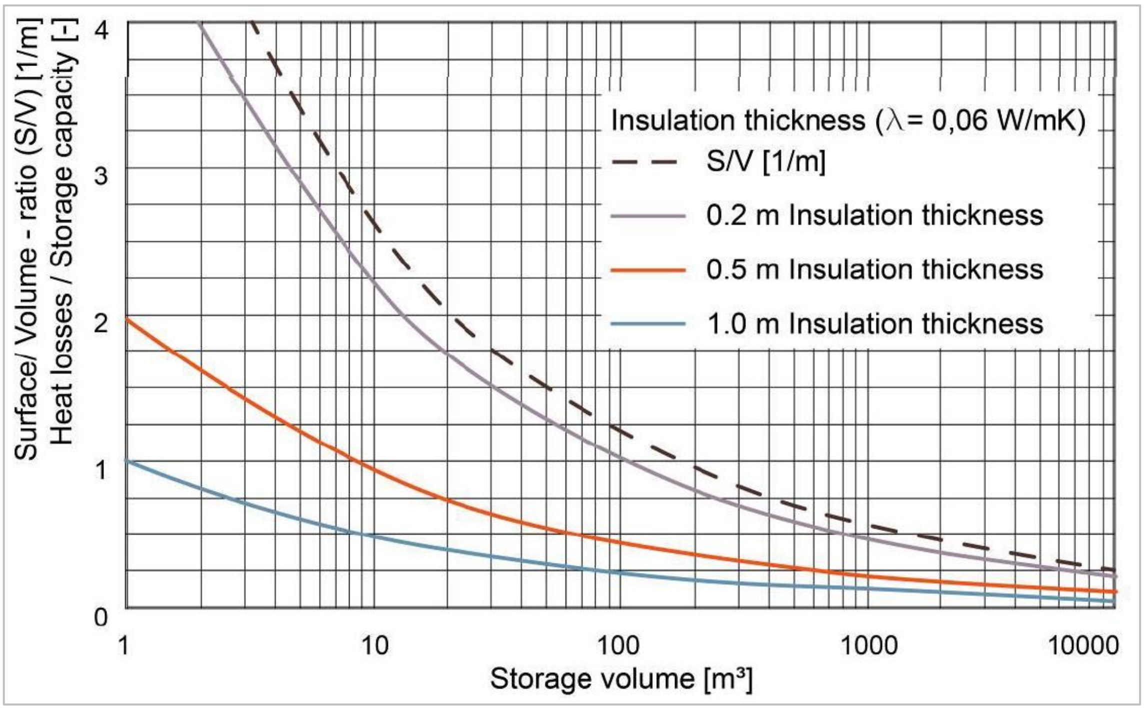


Figure 4. The relation between A/V-ratio and volumetric heat losses. (IEA DHC 2018, 22.)

The borehole storage can be heated up to 80 °C but due to heat losses to the surrounding material, the temperature level of the storage decreases. The system return temperatures are low and limit the system integration, which can be resolved by adding a heat pump to raise the supply temperature to the heating system level. (Mangold et al 2016, 18; Reuss 2015, 122.)

BTES system consists of long boreholes drilled into the ground up to 100 m and heat is transferred to and from the circulating flow. The working fluid circulates in each borehole inside a U-tube linked to the central piping system in the surface. For more efficient heat exchange double U-tube systems can be used. The fluid is usually water mixed with alcohol or glycol, which prevents the fluid from freezing in low temperatures. The storage is charged during the cooling period by pumping heated fluid down to the boreholes, where the heat is transferred from the fluid to the ground before it returns to the surface. During the heating cycle the flow is reversed and the heat is transferred from the ground to the fluid. Cold working fluid heats up in the boreholes and heat is pumped up to the surface, where it is used as heat source for heat pump or directly to domestic water or space heating. Side view of a BTES borehole with a single U-tube is shown in Figure 5. (Lee 2013, 95.)

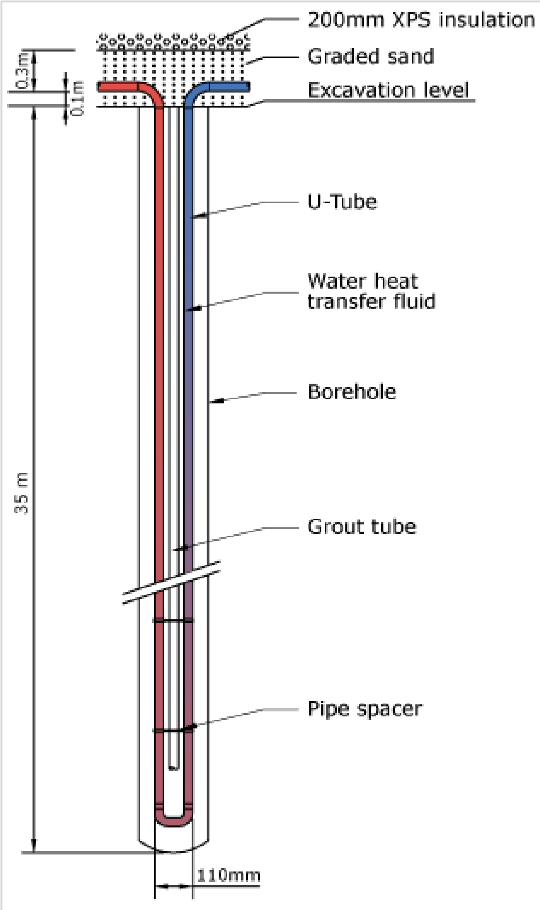


Figure 5. Sideview of a BTES tube. (Drake Landing Solar Community n.d.)

Alternatively, an open system can be used. In an open system the working fluid is injected through an open-end-pipe in the bottom of the hole and extracted with another pipe with open end at the top of the hole (Nielsen 2003, 7.) Because the working fluid flows inside the hole instead of tubes, there is a possibility of circulating fluid leaking to the surroundings. That may cause problems in water chemistry of the system, when the heat transfer fluid gets in contact with the surrounding rock (Nordell 1994, 25.)

The BTES system consists of several boreholes in a quadric or a circular pattern. The hexagonal pattern has more thermally optimal geometry, but the square pattern is simpler to construct. The holes are usually drilled vertical but can also be drilled slightly inclined, if the available land area is small. The spacing between boreholes depends from the thermal properties of the bedrock or the ground. Typical distance between boreholes in Scandinavian rock types is 6–8 m. (Nielsen 2003, 8; Nordell 1994, 22–23.)

The ground at the storage site needs to be drillable and have relatively high heat capacity and thermal conductivity. Typically, the heat capacity should be around 15–30 kWh/m^3. The hydraulic conductivity of the ground needs to be low and the groundwater flow should be less than 1 m/a. Due to intensive drilling up to 100 m, BTES is relatively expensive compared to other UTES types, as the drilling cost is around 20–25 % of total investment cost. Other possible limitations at the site are imbalances through thermal masses and thermal fluctuations in the underground hydrogeological structures. (Kalaiselvam & Parameshwaran 2014, 151–155.)

The storage is usually constructed from double or singular U-pipe borehole heat exchangers, preferably in a hexagonal formation. The storage can be expanded concentrically, if the capacity needs to be increased later. Other notable key points in the construction are the need for heat insulation – e.g. foam glass gravel or shells, and the protecting sealant foil open to vapour diffusion. The hydraulic connection at the site and to the surroundings should be minimised. (Mangold et al 2016, 49.)

2.4 ATES

ATES systems take advantage of the existing ground water reservoirs and utilize them to work as a thermal energy storage for heat and cold. The storage consists of groundwater and the surrounding material, and the heat capacity of the combination is higher than the heat capacity of the ground alone. The ATES functions as an open loop geothermal system with minimum of two wells: cold and warm. As the required system capacity increases, the number of wells increases. Cold or heat is extracted from the well in demand. During the heating cycle the heat is extracted from the warm well and returned to the cold well in lower temperature and vice versa as shown in Figure 6. (Mangold et al 2016, 22; Nordell et al 2015, 88–89.)

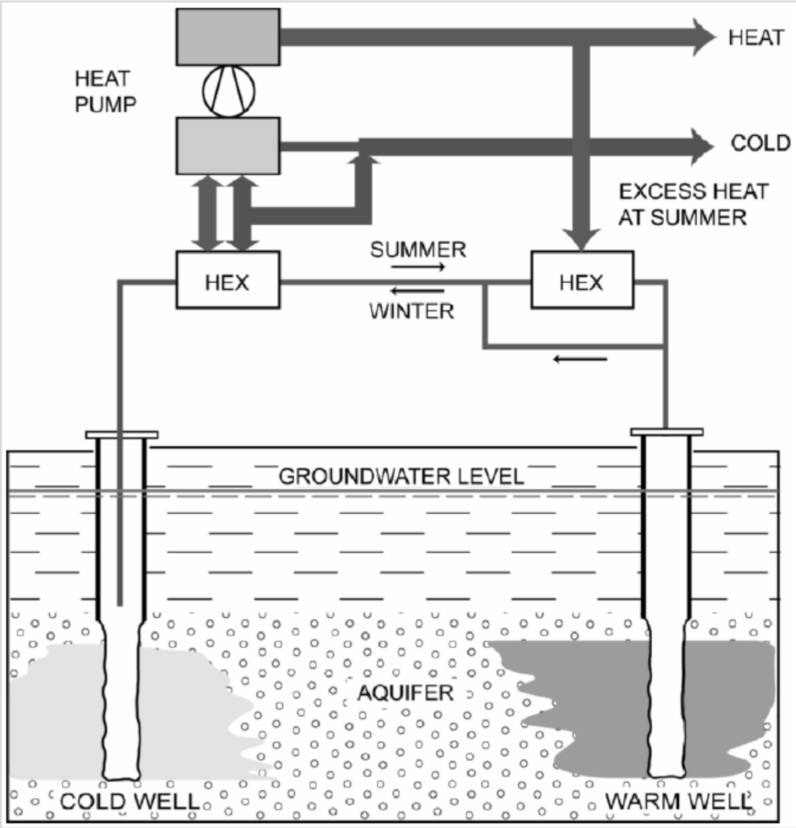


Figure 6. ATES and heat pump system configuration. (Andersson 2007, 156.)

ATES system consists of wells, connecting piping, heat exchangers and cold/heat supplier (Figure 6). The storage can be installed in unconsolidated ground material, like sand or gravel aquifers, or in aquifers in rock fractures as long as the aquifer is enclosed by geological formations. The geological formations prevent the water from escaping the storage. The volume requirement depends on the size of the water reservoir as well as on the amount of energy wanted to be stored. Though, the underground reservoir has to reach the minimal required volume and layer thickness, so that it can be utilised as a storage. (Mangold et al 2016, 23; Nordell et al 2015, 87–88.)

The lowest operating temperature of an ATES system is 5 °C. Since the working fluid is water, the system cannot operate under the freezing temperature of water. The storage functions either in low, medium or high temperatures, depending on the injection temperature and depth. For high temperature system the injected temperature is above 60 °C, for medium temperature system between 30–60 °C and for low temperature system below 30 °C. Low temperature ATES are most commonly applied for combined heating and cooling system. Low temperature systems are utilised especially in Netherlands with circa 2

500 operating storage systems. (Kallesøe & Vangkilde-Pedersen 2019, 50; Nordell et al 2015, 89.)

ATES systems can offer direct cooling energy for buildings but for space heating the supply temperatures are often too low. The increase in supply temperature would lead to high thermal losses caused by greater temperature difference between the surrounding ground and the reservoir. ATES can be used for heating when combined with a heat pump resulting higher coefficient of performance of the heat pump, than ground-coupled heat pump without a storage system. (Nordell et al 2015, 89–90.)

ATES systems are one of the most cost-effective thermal storage types with shortest pay-back time, because the application requires less drilling compared to BTES of the same capacity. However, the utilisation of the reservoirs requires more preliminary studies from the geological site and more intensive monitoring during operation. Also, the authorization process is more extensive compared to other UTES applications. (Mangold et al 2016, 23.)

Existence of a natural aquifer layer with high hydraulic conductivity and confining ground layers on the top and below the reservoir at the site are required. There should be low or no groundwater flow in the ground and the reservoir should have an appropriate water chemistry for high temperatures. The required thickness of the reservoir is 20–50 m. Limitations for ATES application are the inconsistency of the quality of the reservoir and possible scale formation in the wells. Groundwater protective actions and legislation also restrain the utilization of existing groundwater reservoirs. The reservoirs in Finland are categorized in applicable or important water resources. Important water resources are utilized for water supply or for domestic water use and therefore are not suitable for ATES application (Ymparisto.fi, 2018.) Other limiting factors are possible health issues caused by bacteria growth in low operating temperatures, pressure losses in the heat pump or in the heat exchanger and fluctuations of the groundwater table caused by the storage application. (Kalaiselvam & Parameshwaran 2014, 151.)

Water protection measures and other important key points need to be considered in planning and construction of ATES. The storage consists of two or more wells with winding wire filter and the materials used in the storage circuit need to be highly corrosion resistant. During the construction process, any oxygen entering the store has to be prevented. The water treatment depends from the hydrochemistry of the location, which requires regular sampling and analyse of the water. (Mangold et al 2016, 49.)

2.5 PTES

Pit thermal energy storages can use water, soil, rock-air or rock-water combinations as storage material. The storage system consists of a large enclosed and insulated pit, which is partially or fully excavated in the ground into the depth of 5–15 m (Figure 7). The top of the storage is flat and has usually a floating cover. The storage configuration is cylindrical or conical. The cylindrical shape minimizes thermal losses and eliminates corner effects, whereas truncated conical shape reduces thermomechanical stress on the walls and has better A/V-ratio. The slope of the pit walls and the storage depth depend on the surrounding ground material and its density. The excavation of the storage increases construction costs of the buried pit but removes the need for additional insulation layers on the top. (Dahash et al 2019, 303; Mangold et al 2016, 15; Sigh et al 2019, 1120.)

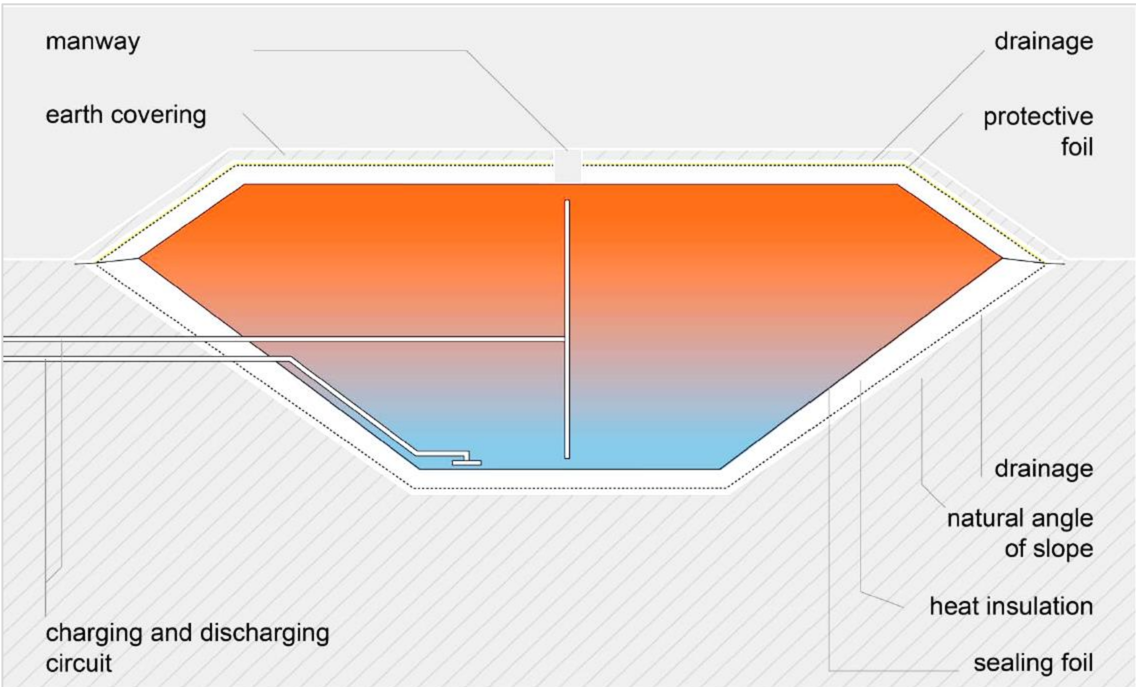


Figure 7. Example of PTES construction. (Mangold et al 2016, 15.)

The heat is conducted in the storage material directly or indirectly through wells or pipelines and extracted on demand. If the storage material is purely water, a stratification device is used for discharging and charging of the storage. The heat capacity of the storage decreases as the ratio of solid material to water increases, thus the volume required for the same heat content increases. The combination of solid material and water reduces the stratification of the storage. However, the use of solid-water combination increases the load capacity of the roof of the storage. The temperate level of the pit storage depends on the stability of the sealing, ranging from 5 to 95 °C. (Mangold et al 2016, 17; IEA DHC 2018, 15.)

Geological requirements for a pit storage are stable ground conditions and no or low groundwater flow. The depth of the storage is moderate and ranges from 5 to 15 m. In the construction phase of the storage the cover is chosen based on the storage material. A floating cover is installed on a water filled pit and a cantilevered roof on a gravel-water filled bed. The sealing is usually welded with an aluminium-plastic composite or with a plastic sheet. Expanded glass granulate or similar is used for heat insulation of the storage. A stratification system with cups is used for direct charging and discharging and coils for indirect charging and discharging in water-filled pits. (Kalaiselvam & Parameshwaran 2014, 155; Mangold et al 2016, 49.)

2.6 Tank Thermal Energy Storage

Water has a high heat energy storage density and weight compared to other heat storage materials. In addition, it is a harmless and cheap material, which is easy to store and operate between boiling and freezing temperatures. The density decreases with temperature, which causes hot water to rise upwards and cold water to move downwards. As the kinematic viscosity decreases with temperature increase, the temperatures in the hot water levels equalize quicker than in lower levels. That creates a stratification in the storage with large temperature differences in the hot water store. Consequently, hot water can be collected from the top of the storage and cool water supplied to the bottom. (Furbo 2015, 31–35.)

To minimize storage volumes, the heat content must be maximized. The geometry of the store and the insulation need to be optimized to reduce thermal losses. Since the volume related thermal losses are high, the volume of the storage should be minimum of 1 000 m^3 to reach acceptable thermal efficiencies. Typical tank thermal energy storage size ranges from 2,750 m^3 to 12,000 m^3. (Furbo 2015, 35–57; Mangold et al 2016, 14.)

The storage consists largely from reinforced concrete containers, which are sealed with stainless or black steel. The floor and walls can be insulated with foam glass gravel and roof with expanded glass granulate. The tank can be constructed above, partly or fully underground. The ground conditions at the site need to be solid and there should be low or no ground water flow at the construction site. The depth of the buried storage ranges from 5 to 15 m. An example of a thermal tank installation is shown in Figure 8. (Mangold et al 2016, 13; Kalaiselvam & Parameshwaran 2014, 155.)

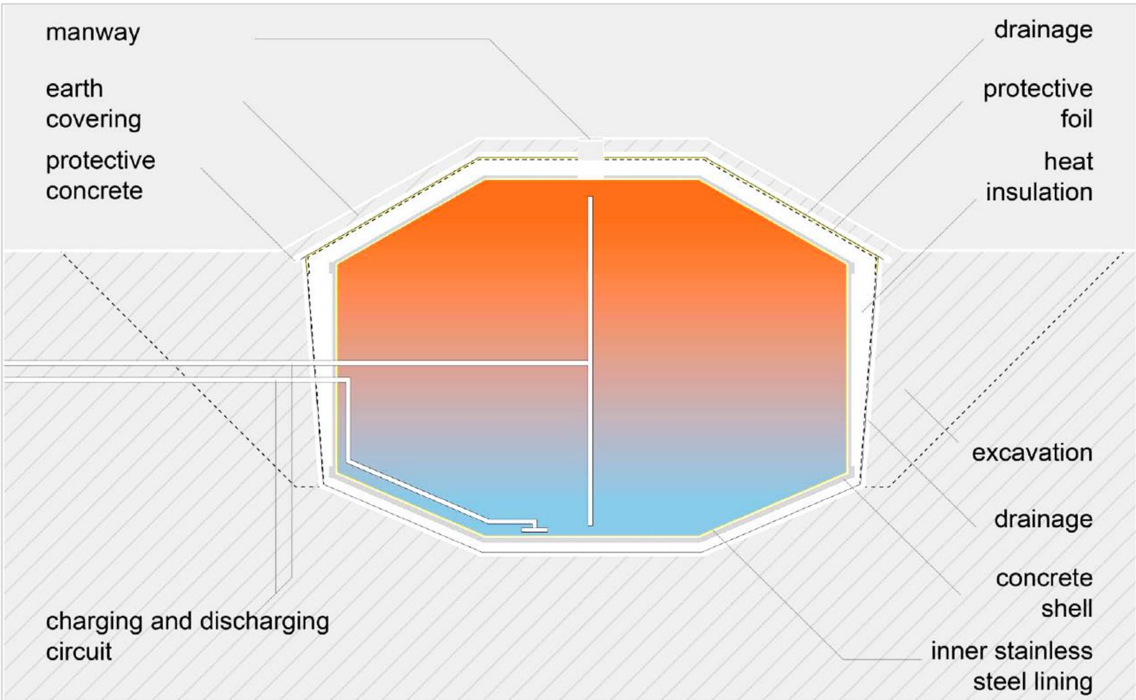


Figure 8. Example of TTES construction. (Mangold et al 2016, 13.)

In an unpressurized storage tank, the storage medium can be heated up to 95 °C, but in pressurised storage tanks the temperatures can be significantly higher. The tank is charged and discharged with pipelines. A stratification device is used to charge the heated water into the right temperature zone to prevent mixing of the stratification layers. During extraction, the heat is extracted from the hottest part of the storage and cold is supplied to the bottom. (Mangold et al 2016, 14.)

The specific heat capacity of storage tanks is high compared to other SeTES and the discharge temperature level is high enough for space and domestic hot water (DHW) heating. In addition, the access time of TTES is shorter compared to other storage types and the heat can be extracted in high volume flows following the demand. However, the construction costs of the tank storage are high due to insulation, structure and extensive excavation, if the tank is buried. High investment cost decreases the economic potential of the storage system. (Dahash et al 2019, 301; Mangold et al 2016, 14.)

In the construction, the concrete vessel is cast at the site or made from prestressed precast. In the case of a pressurized tank, the vessel has to resist pressurized conditions. All surfaces of the storage must be insulated effectively to avoid thermal losses. The sealing can be pre-mounted on prefabricated parts and welded at the site. For protection, the insulation of the system must be open to vapour diffusion and has to tolerate technical hazards. (Mangold et al 2016, 49.)

2.7 Summary of the studied technologies

The main advantages and disadvantages of the introduced storage types as well as the usual storage materials are listed in Table 3.

Table 3. Advantages and disadvantages of chosen TES technologies.

Tank TES	**Pit TES**	**Borehole TES**	**Aquifer TES**
water	water (gravel-water)	soil or bedrock	saturated sand-water
+ high thermal capacity + can be used as buffer storage + high operating temperature + high charge/discharging power + thermal stratification + flexible design of geometry + easy maintenance/repair - size limit <100 000 m^3 - high construction costs	+ moderate construction costs + high thermal capacity (water) + no size limits + can be used as buffer storage + high operating temperature + high charge/discharge power - expensive and complex cover - slope angle limited design - difficult or no possibility to maintenance	+ low construction costs + expandable - low thermal capacity - low operating temperature - low charge/discharge power - requires a buffer storage - requires a heat pump for high temperatures - only top is insulated - difficult or no possibility to maintenance - geological limitations	+ lowest construction costs + moderate thermal capacity - low operating temperature - low charge/discharge power - requires a heat pump for high temperatures - buffer storage recommended - geological and hydrological limitations - no thermal insulation - extensive pre-investigations

3 CASE BUILDINGS

The case real estates are located in South-Karelia in Lappeenranta and Imatra and are owned by the cities. The data from the real estates and their energy consumptions are collected and simulated for the *Public-Private Partnership in real estate energy efficiency improvements and finance* –project. The data and results of the project are used in this thesis to investigate the potential of each storage option for the case real estates.

3.1 Energy use in the case real estates

Public real estates have high heat energy demand, which has a significant impact on their annual operation costs and environmental effects. Heating covers 64 % of the annual energy demand in the case real estates in Lappeenranta (Figure 9) and 58 % in the real estates in Imatra (Figure 10). Both cities purchase renewable and carbon neutral electricity, hence, the only source of emissions for the real estates is heating. The emissions can be reduced by shifting to higher consumption of electricity and by reducing total energy consumption. This can be performed by switching the heating system from conventional energy sources or district heating to heat pumps utilizing geothermal energy or heat energy from ambient air.

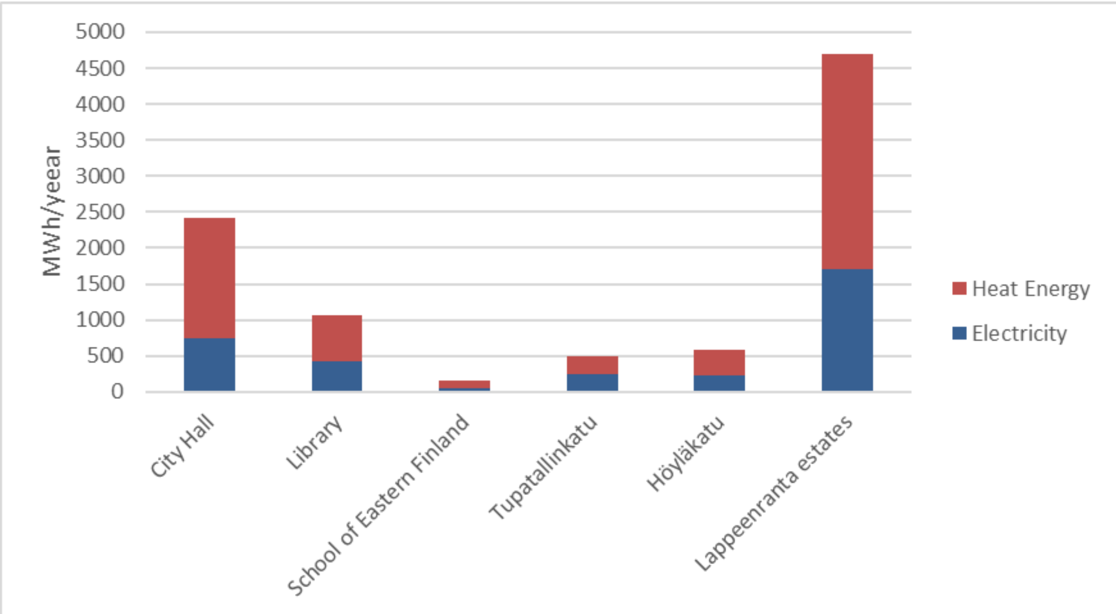


Figure 9. Energy use in Lappeenranta real estates. Data: *Public-Private Partnership in real estate energy efficiency improvements and finance* –project.

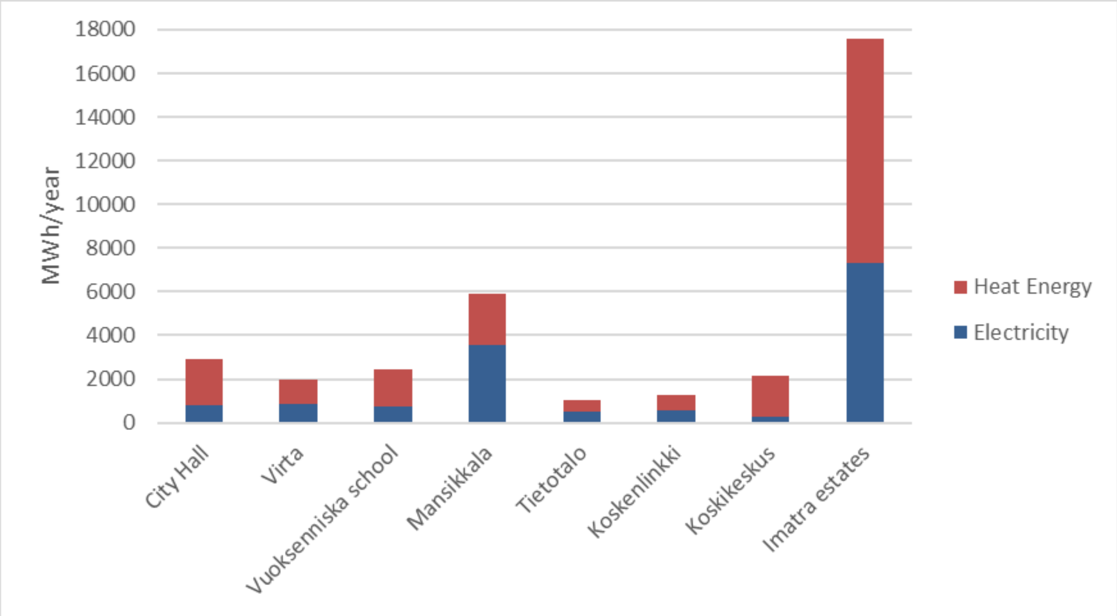


Figure 10. Energy use in Imatra real estates. Data: *Public-Private Partnership in real estate energy efficiency improvements and finance* –project.

In the project it was found that a heat pump installation can reduce the need of external heat demand significantly and can economically cover circa 80 % of the heat consumption in the project real estates. The yearly emissions can be reduced even further, when the external heat demand is covered by a seasonal storage. With smart energy management, real estates can even become zero-emission buildings (ZEB) using only renewable energy sources, such as waste heat and solar energy.

3.2 Geological and hydrological conditions

To find the most attractive energy storage solutions for each case, the real estates are evaluated based on available area, soil depth and structure, bedrock material and existence of an aquifer. Geological information from Imatra and Lappeenranta area is available in Maankamara map service from *Geological Survey of Finland* (Geologian tutkimuskeskus, GTK). Information from existing aquifers is obtained from *Joint website of Finland's environmental administration* and the essential features are listed in Table 4 and 5.

Table 4. The case real estates in Lappeenranta and essential features. (GTK, Maankamara, n.d.; Ymparisto.fi 2014b)

Lappeenranta	Available area [m²]	Soil depth [m]	Soil texture	Bedrock	Aquifers
1. City Hall	6 691	50	sand	biotite	III
2. Library	2 079	50	sand	biotite	III
3. School of Eastern Finland	32 988	10-50	sand	limestone, granite	I
4. Tupatallinkatu	28 272	10	sandy till	granite	-
5. Höyläkatu	20 217	10	finesand	granite	-

Groundwater classifications: I important domestic water reservoir, II applicable for other purposes, also for domestic water use, III other (Ymparisto.fi 2018.)

Table 5. The case real estates in Imatra and essential features. (GTK, Maankamara, n.d.; Ymparisto.fi 2014a.)

Imatra	Available area [m²]	Soil depth [m]	Soil texture	Bedrock	Aquifers
1. City Hall	24 880	10	clay	granite	-
2. Cultural Center Virta	17 667	10	clay	granite	-
3. Vuoksenniska School	32 839	50	esker (gravel)	biotite	III
4. Mansikkala	11 917	10	silt	microcline	-
5. Tietotalo	1 380	10	clay, till	microcline	-
6. Kosken linkki	2 248	10	clay	microcline	-
7. Koskikeskus	4 669	10	till	microcline	-

Groundwater classifications: I important domestic water reservoir, II applicable for other purposes, also for domestic water use, III other (Ymparisto.fi 2018.)

Based on the features and limitations of chosen technologies, suitable technologies are estimated for each case. The limitations caused by the size and location of the real estate are the main restrictive factors for UTES technologies in addition to economical requirements. Preliminary evaluation for each real estate and theoretically feasible TES technologies in Lappeenranta and Imatra case real estates are presented in Table 6 and 7.

Table 6. Theoretical feasibility of TES technologies in Lappeenranta real estates

Lappeenranta	TTES	ATES	BTES	PTES
1. City Hall	not applicable, city centre	not applicable, city centre	not applicable, city centre	not applicable, city centre
2. Library	not applicable, city centre	not applicable, city centre	not applicable, city centre	not applicable, city centre
3. School of Eastern Finland	applicable	not applicable, class I aquifer	not applicable, restricted area	applicable
4. Tupatallinkatu	applicable	not applicable, no aquifer	applicable	applicable
5. Höyläkatu	applicable	not applicable, no aquifer	applicable	applicable

Table 7. Theoretical feasibility of TES technologies in Imatra real estates.

Imatra	TTES	ATES	BTES	PTES
1. City Hall	applicable	not applicable, no aquifer	applicable	applicable
2. Cultural Center Virta	applicable	not applicable, no aquifer	applicable	applicable
3. Vuoksenniska School	applicable	possibly applicable, class III aquifer	applicable	applicable
4. Mansikkala	applicable	not applicable, no aquifer	applicable	applicable
5. Tietotalo	not applicable, small real estate	not applicable, no aquifer	not applicable, small real estate	not applicable, small real estate
6. Kosken linkki	not applicable, small real estate	not applicable, no aquifer	not applicable, small real estate	not applicable, small real estate
7. Koskikeskus	not applicable, small real estate	not applicable, no aquifer	not applicable, small real estate	not applicable, small real estate

3.3 Additional heat demand after energy efficiency improvements

Energy efficiency improvements from renovation and applicable technology are estimated earlier in the *Public-Private Partnership in real estate energy efficiency improvements and finance* –project and feasible technologies for these cases are evaluated to be either air-to-water heat pump (AWHP) or ground source heat pump (GSHP), improved heat recovery system and photovoltaics panels. The heat pump can cover economically circa 80 % of the heat demand. Thermal energy storage options can support the heating system by applying additional heat source during high energy demand, alternative to conventional energy or district heating.

The storage size is estimated based on the required capacity of additional heat source. Same energy efficiency improvements are chosen for each real estate, so the results are more comparable with one another, even though the same energy efficiency actions are not recommended for all cases. For these estimations, the stored energy is chosen to be the required additional energy needed after AWHP installation.

Thermal energy storages work between heating and cooling cycle charging and discharging thermal energy. The storage is charged with heat energy from cooling and stored heat from summer is used for heating in winter. As the heat is discharged from the storage, it simultaneously stores cold for cooling in summer.

The theoretical cooling demand is estimated from heat losses and internal heat loads of the building. Cooling is required, when heat loads from solar radiation, humans, electric equipment and lighting are greater than losses from structure and leakage air (Equation 1.) Instead of removing heat to ambient air through a water cooler or other cooling machine, it can be utilized later, when the heat is charged in the storage while cold is discharged for cooling. The theoretical cooling demand is approximated followingly

$$Q_{\text{space}} = Q_{\text{heat loads}} - Q_{\text{heat losses}} \tag{1}$$

where $Q_{\text{heat loads}}$ are heat loads from heat sources [kWh]

$Q_{\text{heat losses}}$ are heat losses through ventilation and structures [kWh].

Specific internal heat sources differ between building types according to usage type and capacity utilization rate. Relevant heat sources in the case real estates are heat loads from humans, lighting, appliances and solar radiation (Equation 2)

$$Q_{\text{heat loads}} = Q_{\text{humans}} + Q_{\text{lighting}} + Q_{\text{appliances}} + Q_{\text{solar}} \tag{2}$$

where Q_{humans} is heat load from people inside the building [kWh]

Q_{lighting} is heat load from lighting [kWh]

$Q_{\text{appliances}}$ is heat load from appliances [kWh]

Q_{solar} is heat load from solar radiation [kWh].

Typical values for internal heat loads and usage hours for real estates with different usage type and hours are listed in Table 8.

Table 8. Typical usage time, capacity utilization and internal heat loads in different usage groups. (Ympäristöministeriö 2017, 3-7.)

Usage group	Time	Time of use		Capacity utilization	Internal heat load per heated area		
		h/24h	d/7d		Lighting W/m^2	Appliances W/m^2	Humans W/m^2
1) Small residential building	00:00-24:00	24	7	lighting 0.1 other 0.6	6	3	2
2) Residential apartment building	00:00-24:00	24	7	lighting 0.1 other 0.6	9	4	3
3) Office building	07:00-18:00	11	5	0.65	10	12	5
4) Commercial building	08:00-21:00	13	6	1	19	1	2
5) Hotel, caring institution	00:00-24:00	24	7	3	11	4	4
6) School, kindergarten	08:00-16:00	8	5	0.6	14	8	14
7) Sport hall	08:00-22:00	14	7	0.5	10	0	5
8) Hospital	00:00-24:00	24	7	0.6	7	9	8

The capacity usage percent is calculated according to the typical values for each usage type from Table 8. The time of use is calculated as follows

$$n_{\mathrm{t}} = \frac{time\ of\ use\ [h/24h] \cdot time\ of\ use\ [d/7d]}{24h \cdot 7d} \tag{3}$$

where n_{t} is the time of use per week [-]

h are hours in a day [-]

d are days in a week [-].

Corresponding heat losses in this study are heat loss through structure, ventilation and leakage air (Equation 4)

$$Q_{\text{heat losses}} = Q_{\text{structure}} + Q_{\text{ventilation}} + Q_{\text{leakage air}} \tag{4}$$

where $Q_{\text{structure}}$ is heat loss through building envelope [kWh]

$Q_{\text{ventilation}}$ is heat loss from ventilation [kWh]

$Q_{\text{leakage air}}$ is heat loss from leakage air [kWh].

Heat loss through structure is calculated with Equation 5, when the thermal transmittance through structure type and area of each structure type are known

$$Q_{\text{structure}} = \Delta T \cdot \Sigma(U \cdot A) \cdot d \cdot 24h/d \tag{5}$$

where ΔT is temperature difference between indoor and ambient air temperature [K]

U is thermal transmittance of a structure type [W/(m^{2}K)]

A is area of each structure type [m^2]

d is the amount of days in a month.

Heat loss through ventilation is calculated with Equation 6, when the average supply air flow is known

$$Q_{\text{ventilation}} = \rho_{\text{air}} \cdot c_{\text{p,air}} \cdot q_{\text{v,supply}} \cdot (1-\eta_{\text{t}}) \cdot \Delta T \cdot d \cdot 24h/d \tag{6}$$

where ρ_{air} is density of air [kg/m^3]

$c_{\text{p,air}}$ is heat capacity of air [J/(kgK)]

$q_{\text{v,supply}}$ is average supply air flow [m^3/s].

Heat loss through leakage air is estimated from leakage air through surface (Equation 7)

$$Q_{\text{leakage air}} = \rho_{\text{air}} \cdot c_{\text{p,air}} \cdot q_{\text{v,leakage air}} \cdot d \cdot 24h/d \tag{7}$$

where $q_{\text{v,leakage air}}$ is leakage air flow [m^3/s].

Internal heat loads and heat load from solar radiation and heat losses through structure, ventilation and leakage air are approximated previously in Knuutila's (2019) Excel-tool for energy efficiency improvements. The results from the calculations are used as input for this study and the total cooling demand for each real estate is presented in Table 9.

Even though heating period in Finland is long compared to cooling period in summer, cooling demand can exceed heating demand in an annual level. If the heat from cooling is deficient to cover the heating demand of a real estate, an additional heat source is needed. Additional heat energy can be generated with the heat pump or obtained from solar collectors. After the installation of the AWHP, it can be used to charge the storage system in summer months when the heat demand of the real estate is low. The maximum heating power relative to nominal power can be estimated from Equation 8

$$P_{\text{H,max}} = f_{\text{max}} \cdot \eta_{\text{v}} \cdot \rho_{\text{s}} \cdot V_{\text{s}} \cdot dh \tag{8}$$

where $P_{\text{H,max}}$ is the maximum heating power [kW]

f_{max} is the frequency of the compressor [Hz]

η_{v} is the volumetric efficiency of the compressor [-]

ρ_{s} is the density of refrigerant in the suction side [kg/m^3]

V_{s} is suction volume [m^3]

dh is the enthalpy change in the condenser [kJ/kg].

The frequency of the compressor is obtained from the electrical grid, which is assumed to be 50 Hz during maximum power production. The density of the refrigerant at the suction side is defined in evaporator conditions and it changes as a function of ambient air temperature. The refrigerant is assumed to be R410a, hence, the minimum evaporation temperature of the refrigerant is assumed to be -25 °C in a typical heat pump (Grassi 2018, 41). The monthly average temperature in Lappeenranta and Imatra is measured to be at its lowest in January, -7.6 °C. In this case is assumed that the temperature stays above -15 °C, since the heat for charging is produced during summer, so the decrease in ambient air temperature does not affect on the pump performance dramatically.

The enthalpy change in the condenser stays nearly constant, when the isentropic efficiency of the compressor is assumed constant and sub cooling in the condenser is neglected. By assuming the volumetric efficiency of the compressor and the maximum suction volume to stay constant, the maximum power production becomes a function of ambient air temperature (Equation 9)

$$P_{\mathrm{h,max}} = C \cdot \rho_{\mathrm{s}} \cdot (T) \tag{9}$$

where C is constant [W/(m^{3}kg)].

The relative power of the heat pump is simulated as a function of temperature for heat pump optimization in the *Public-Private Partnership in real estate energy efficiency improvements and finance* –project by using Thermophysical Property Library CoolProp. The maximum relative power produced as function of temperature and the correlation are plotted in Figure 11.

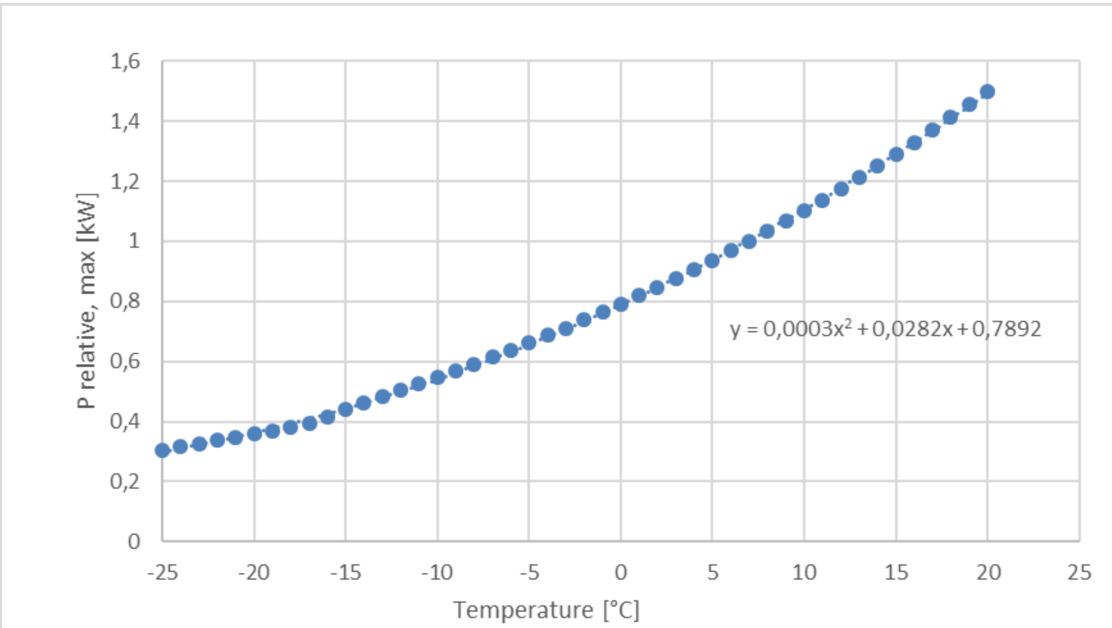


Figure 11. Relative power of the heat pump as a function of temperature.

The size of the AWHP is optimized for each real estate previously in the project and the maximum thermal output is calculated at standard conditions (7 °C/35 °C). The theoretical excess heat is approximated from the maximum power output during the months, when ambient air temperature is higher than 10 °C (Equation 10). The energy consumed by the heating system is reduced from the maximum power output.

$$E_{\mathrm{excess,max}} = P_{\mathrm{h,max}} \cdot t - E_{\mathrm{h}} \tag{10}$$

where $E_{\mathrm{excess,max}}$ is the energy available for charging [kWh]

t is time when monthly average temperature > 10 °C [h]

E_{h} is the heat energy consumption of the building [kWh].

Heating demand for an additional heat source after AWHP installation, energy from cooling and excess heat energy are listed for each case real estate in Table 9 and 10.

Table 9. Additional heat demand and potential heat sources in Lappeenranta cases.

Lappeenranta	Additional heat demand [kWh]	Cooling demand [kWh]	$E_{\mathrm{excess,\,max}}$ [kWh]
1. City Hall	200 645	385 000	1 148 919
2. Library	74 744	237 000	451 792
3. School of Eastern Finland	16 932	34 214[1]	96 809
4. Tupatallinkatu	37 571	3 000	195 195
5. Höyläkatu	66 530	61 000	318 991

[1]Heat load from humans is assumed zero during holiday season in June and July.

Table 10. Additional heat demand and potential heat sources in Imatra cases.

Imatra	Additional heat demand [kWh]	Cooling demand [kWh]	$E_{excess, max}$ [kWh]
1. City Hall	260 029	369 000	1 494 426
2. Cultural Center Virta	173 196	407 000	821 444
3. Vuoksenniska School	210 424	83 162[1]	1 331 849
4. Mansikkala	324 263	200 000	1 790 949
5. Tietotalo	68 622	177 000	1 630 893
6. Kosken linkki	82 376	183 000	515 259
7. Koskikeskus	319 297	312 000	544 292

[1]Heat load from humans is assumed zero during holiday season in June and July.

From the tables can be seen, that the cooling demand covers the additional heat demand in three cases in Lappeenranta and in four cases in Imatra. The installed AWHP can be used to supply required heat energy for charging during the cooling period in cases, where energy from cooling is not enough.

4 TECHNO-ECONOMIC OPTIMIZATION AND ANALYSIS OF SELECTED STORAGE TYPES

The selection of the storage type is based on the hydrological and geological conditions of the real estate, requirements from the system-side of the real estate, local conditions including available space and possible restrictions. The choice is made according to the cost-effectiveness of the storage type (Mangold et al 2016, 44). The key features considering geological requirements and construction are discussed in Chapter 2.

The primary limitation in Lappeenranta City Hall and Library is the lack of available surface area and central location. The same limitations apply also in Tietotalo, Koskenlinkki and Koskikeskus real estates in Imatra. In these cases, the studied storage types are not found technically applicable and further calculations for these real estates are not included in this study. For other cases, the selection is made between ATES, BTES, PTES and TTES systems. An Excel tool is developed for evaluating and comparing the studied storage options and calculations are ran for each real estate, where these technologies are technically feasible. Calculations are demonstrated with the following case examples.

4.1 Thermal properties of local ground materials

Storage material selection is based on the ability to store and restore energy in mass, which is estimated according to formula (11)

$$Q = m \cdot c_\mathrm{p} \cdot \Delta T \qquad \text{or} \qquad Q = \rho \cdot c_\mathrm{p} \cdot V \cdot \Delta T \tag{11}$$

where m is mass [kg]

c_p is specific heat capacity [kJ/(kgK)]

ΔT is temperature difference between state 1 and 2 [K]

ρ is the density of the storage medium [kg/m^3]

V is the total volume of storage material [m^3].

Typical storage types are water-, rock- and ground based, where the storage medium is cheap and easy to control. The storage systems are reliable but have considerable heat losses due to relatively low energy density, so the volumes should be large to compensate the thermal losses relative to volume.

Heat capacity and thermal conductivity from soft ground material can be estimated by its composition. Natural solid materials consist of basic minerals, water, soil and air. The density of air can be ignored due to its small density compared to other compositions. The density of all basic minerals is circa 2 650 kg/m^3 and the heat capacity is close to 755 J/kgK. For water, the density is assumed to be 1 000 kg/m^3 and the specific heat capacity 4 200 kg/m^3. The specific heat capacity of the ground material can be calculated as follows (Leivo et al 2002, 19–20)

$$C = f_\mathrm{g} \cdot C_\mathrm{g} + f_\mathrm{w} \cdot C_\mathrm{w} \tag{12}$$

where f_g is volumetric share of ground mineral [-]

C_g is heat capacity of ground mineral [J/(kgK)]

f_w is volumetric share of water [-]

C_w is heat capacity of water [J/(kgK)].

The amount of solid material in ground material can be calculated from the porousness of the ground type, which is the average share of air calculated as follows (Leivo et al 2002, 20)

$$f_\mathrm{g} + f_\mathrm{w} = 1 - f_\mathrm{a} \tag{13}$$

where f_a is volumetric share of air [-].

The average of total porosity, water content and heat capacity of the ground types at the case real estates in Lappeenranta and Imatra are calculated and listed in Table 11. Heat capacities of the local bedrock materials at the real estates are obtained from literature and are listed in Table 12.

Table 11. Porosities, water contents and heat capacities of local ground types. (Martio 2011, 19; Ronkainen 2012, 25–28)

Ground type	Porosity n	Water content f_w	Heat capacity kJ/kg	Volumetric heat capacity kWh/m^{3}K
Sand	38 %	18 %	1775	0.49
Gravelly till	38 %	14 %	1664	0.46
Finesand	33 %	18 %	1857	0.52
Gravel	38 %	7 %	1467	0.41
Clay	68 %	76 %	3329	0.92
Silt	48 %	31 %	2001	0.56
Till	38 %	13 %	1631	0.45

Table 12. Heat conductivities and capacities of local bedrock materials. (Alanen et al 2003, 13; Kukkonen & Lindberg 1998, 16; University of Minnesota n.d.; Haldar & Tišljar 2014)

	Heat capacity J/kg K	Volumetric heat capacity kWh/m^3 K
Granite	830	0.62
Limestone	840	0.63
Biotite	770	0.58–0.81[1]
Microcline	670–690	0.49[1]
Water	4 180	1.18

[1]Calculated: density 2 700–3 400 kg/m^3 and 2 550–2 630 kg/m^3

4.2 Case 1: Vuoksenniska School

Vuoksenniska School has been built in 1959, and it has a total heated area of 4 484 m^2 and is heated with district heating. The energy efficiency improvement potential in ventilation, insulation and heat pump installation were estimated with the Excel-tool developed in the previous phase of the project (Knuutila 2019). In the second phase of the project the AWHP and GSHP were simulated and optimized for each case real estate and the results were integrated in the Excel-tool.

The heating and cooling demand after before mentioned improvements are used as initial values for energy storage calculations in order to evaluate the maximum potential of the investment. The required storage volume is approximated to store the heat demand not covered by the AWHP. The same improvements are assumed for all case real estates to reach better comparability between cases. The estimated yearly energy demand after before mentioned energy efficiency improvements in Vuoksenniska School and the average monthly temperatures are plotted in Figure 12. Note, that the theoretical cooling demand is estimated with the assumption of no heat load from humans and appliances during summer vacation in June and July (Lappeenranta n.d.c.)

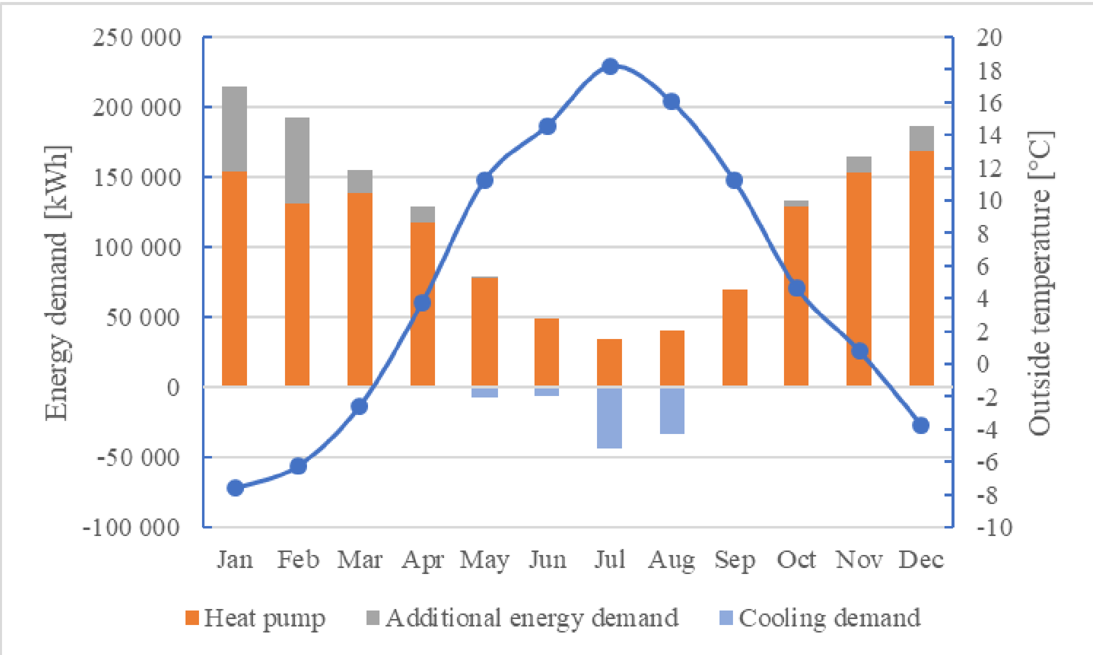


Figure 12. Monthly energy demand of Vuoksenniska School and average ambient temperature of years 2008-2018. Data: *Public-Private Partnership in real estate energy efficiency improvements and finance* –project; Finnish Meteorological Institute 2019.

Vuoksenniska School locates at class III groundwater area (514303 Vuoksenniska), which is classified as “other groundwater area”. Based on the information from Hertta 5.7 database (SYKE, ELY-keskukset n.d.a), the reservoir area is 4.71 km^2 and groundwater formation approximately 2500 m^3/d. Nearby the real estate there are three observation wells offering information about the ground and the groundwater level. The observation wells and location of the school are shown in Figure 13. Finnish Environment Institute (Suomen Ympäristökeskus, SYKE, n.d.b) offers a map service with information on the local bedrock level and stratums. The stratums at the case real estate area are bedrock, groundwater and till. The bedrock level is located in the depth of 41 m and the groundwater is captured between the bedrock and the ground material. The local surface level at the real estate is obtained from Paikkatietoikkuna map service (National Land Survey of Finland, n.d.) (Figure 14).

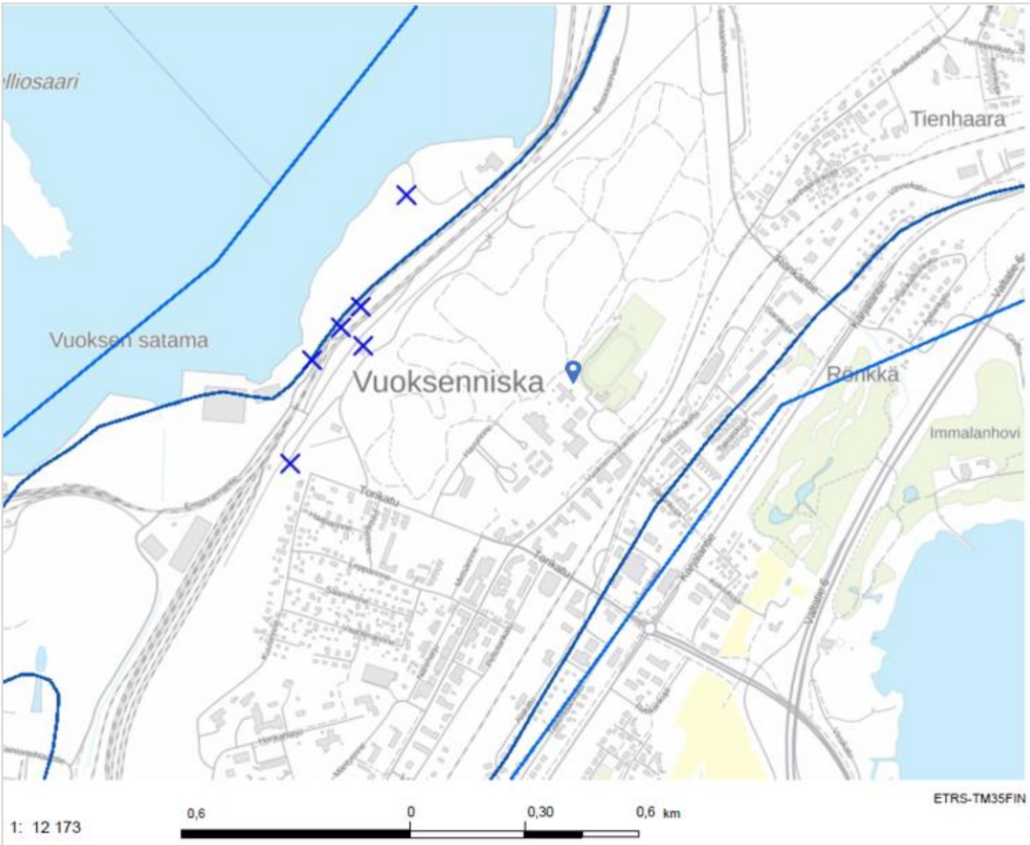


Figure 13. Observation wells (x) and location of the school. (SYKE, ELY-keskukset n.d.a)

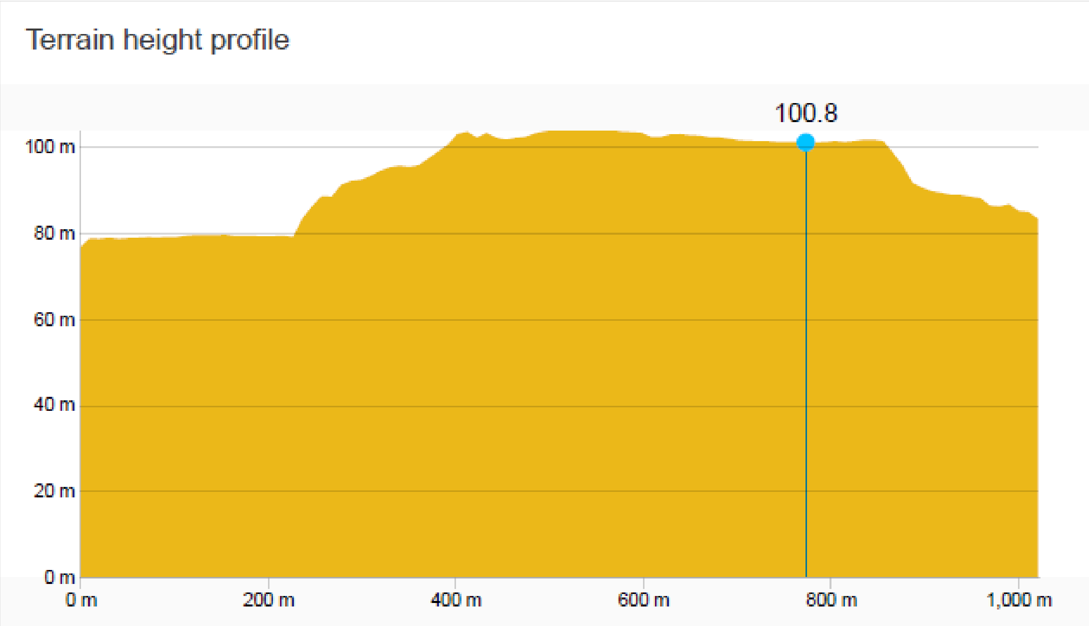


Figure 14. Terrain height profile obtained from Paikkatietoikkuna (National Land Survey of Finland)

Three observation spots (FCG1, FCG2 and FCG3) have reported the groundwater height at Hertta 5.7. and the groundwater level in 31st of October in 2016 was 78.06 m in FCG1, 76.95 m in FCG2 and 77.26 m in FCG3. The average groundwater level was 77.42 m. Paikkatietoikkuna estimates the local surface level at the observation spots to be 81.3 m and 100.8 m at Vuoksenniska School. The thickness of the aquifer is estimated based on the information on groundwater and bedrock levels. The depth of the aquifer can be estimated from local surface level at the case real estate, when assuming the thickness of the aquifer to stay nearly constant throughout the reservoir area.

4.2.1 Input values

Based on available information, the thickness of the groundwater is estimated to be 37 m. The heat capacity of the aquifer is calculated from average porosity (Bloemendal et al 2018, 537)

$$c_{\text{aquifer}} = n \cdot c_{\text{water}} + (1 - n) \cdot c_{\text{gravel}} \tag{14}$$

where n is porosity [-]

c is heat capacity [J/kg].

The geological conditions are obtained from Table 5 and heat capacities are calculated with Equations 12 and 13. The heat demand of the building is estimated based on previous studies made in the project and the theoretical cooling demand is calculated with Equation 1.

ATES and BTES are calculated as low temperature applications with an assisting heat pump. In heat pump calculations COP (Coefficient of Performance) of 4 is used for heating and 3 for cooling (Bloemendal et al 2018, 535.) Cooling is assumed to be executed with a watercooler and nominal COP of 2.7 (RHOSS 2017, 29.)

Electricity cost consist of energy, transfer and energy tax. The electricity price is estimated previously according to the average ELSPOT price in Finland in 2003-2018. The total price of electricity is approximated to be 104.36 €/MWh including energy (37 %), transfer (29 %), energy tax (15 %) and VAT (19 %). The electricity price without VAT is 71.75 €/MWh. (Knuutila 2019, 31)

District heating price consists of required water flow, transfer and energy fees. The fees are charged according to the water flow rate and basic price. The maximum flow rate and the district heating price are estimated previously in the *Public-Private Partnership in real estate energy efficiency improvements and finance* –project. The calculative flowrate in Vuoksenniska School is 8 m^3/h and related district heating cost without VAT is 61.97 €/MWh.

Constant values for the Excel tool are the temperature differences of the storage types and related water equivalents. Storage cycles are calculated from heating and cooling demand, where the heating cycle consists of months with required additional heat source and cooling cycle from other months. Here, the additional energy is assumed to be covered with heat pump during the summer months, when the ambient air temperature is above 10 °C and the heat demand of the building is low. The heat energy is charged in the storage to cover the demand for additional heat source during the heating cycle. The additional heat produced by the heat pump is estimated for each storage type relative to typical cycle efficiencies.

4.2.2 Aquifer Thermal Energy Storage

Additional input values for ATES calculations are the assumed maximum and minimum temperatures of the aquifer within the set temperature difference of 10 K. According to Arola et al (2016, 643), natural groundwater temperature in Finland is 4.9 °C. Thus, the minimum temperature is set to 5 °C and maximum temperature to 15 °C.

The storage volume is calculated from heating volume and approximated thermal efficiency. The heating volume is calculated from the required heating capacity and the approximated temperature difference of the storage 10 K.

$$E_{\mathrm{h}} = c_{\mathrm{w}} \cdot V_{\mathrm{h}} \cdot \Delta\overline{T_{\mathrm{h}}} \cdot \frac{COP_{\mathrm{h}}}{COP_{\mathrm{h}}-1} \tag{15}$$

where	E_{h}	is the required heating capacity [kWh]
	c_{w}	is volumetric heat capacity of water [kWh/(m^{3}K)]
	V_{h}	is the seasonal volume required for heating [m^3]
	$\Delta\overline{T_{\mathrm{h}}}$	is the temperature difference between warm and cold well during cycle [K]
	COP_{h}	is coefficient of performance of the assisting heat pump [-].

The volume required for heating is

$$V_{\mathrm{h}} = \frac{E_{\mathrm{h}}}{c_{\mathrm{w}} \cdot \Delta\overline{T_{\mathrm{h}}}} \cdot \frac{COP_{\mathrm{h}}-1}{COP_{\mathrm{h}}} = 11\ 729\ m^3$$

Efficiencies between 68–87 % are reported from ATES systems in Hague, Netherlands, so average storage efficiency of 77.5 % is chosen for calculations (Gao et al 2017, 3541.) The required volume of the storage is 15 134 m^3 with the chosen efficiency.

Average groundwater extraction and injection flows required for heating and cooling are calculated from storage cycles

$$Q = \frac{V_\mathrm{s}}{t_\mathrm{cycle}} \tag{16}$$

where Q is the groundwater flow [m^3/d]

V_s is the required storage volume

t_cycle is the duration of the heating or cooling cycle [h].

With the assisted heat production, the heating cycle is 243 d and the heating flow is 48.3 m^3/d. The cooling cycle is 122 d and the cooling flow is 124.1 m^3/d. Bloemendal & Hartog (2018, 309–312) have optimized the screen length of one well in their studies on low-temperature ATES systems. The optimal screen length for the calculated volume is

$$L \approx 1.02 \cdot \sqrt[3]{V_\mathrm{s}} \tag{17}$$

where L is the screen length [m]

The thermal radius of the well is calculated from heat capacities and storage geometry

$$R_\mathrm{th} = \sqrt{\frac{c_\mathrm{w} \cdot V_\mathrm{in}}{c_\mathrm{aq} \cdot \pi \cdot L}} \tag{18}$$

where R_th is the thermal radius [m]

V_in is the injected volume during one cycle, here V_in is V_required [m^3].

According to the ATES planning method of Bloemendal et al (2018, 544), the minimum distance between opposite wells is $3R_\mathrm{th}$. Consequently, the minimum distance between wells is 63.0 m. Here, the total screen length for two opposite wells is 48.8 m and the total drilling 97.6 m, when the depth of the aquifer surface is 23.6 m. The geometry of the wells is sketched in Figure 15.

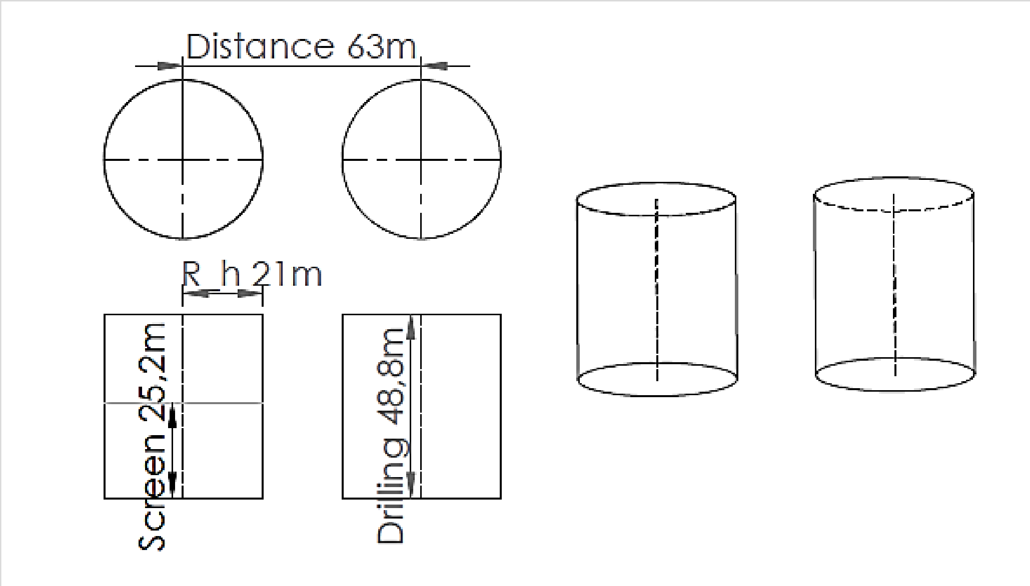


Figure 15. Thermal radius, distance of wells and screen length of ATES made in SolidWorks.

The heating power required from the storage system is estimated from Equation 19 and the heating capacity of the heat pump is calculated from Equation 20. The heating capacity of the aquifer is calculated from Equation 21 (Bloemedal et al 2018, 540.)

$$P_{\mathrm{h}} = \frac{E_{\mathrm{h}}}{t_{\mathrm{h}}} \tag{19}$$

where P_{h} is the heating power of the storage system [kW]

E_{h} is the heating capacity of the storage system [kWh]

t_{h} is the heating period [h]

$$P_{\mathrm{e}} = \frac{P_{\mathrm{h}}}{COP_{\mathrm{hp}}} \tag{20}$$

where P_{e} is the heating power of the heat pump [kW]

COP_{hp} is the coefficient of performance for heating [-]

$$P_{\mathrm{h}} = P_{\mathrm{ATES}} + P_{\mathrm{e}} \tag{21}$$

where P_{ATES} is the heat power of the aquifer thermal energy storage [kW].

Heating water is extracted from the hot well by a submersible pump to a heat exchanger, where it transfers heat from the aquifer to the heating system of the building. The power consumed by submersible pumps depends from the flow rate and the well depth (Equation 22). The overall pump efficiency can be assumed to be 60 %. (Schüppler et al 2019, 6.)

$$P_{\text{submersible pump}} = \frac{Q \cdot \rho \cdot g \cdot h}{3.6 \cdot 10^6} \cdot \eta^{-1} \tag{22}$$

where g is gravity [9.81 m^2/s]

h is the well depth [m]

η is the overall pump efficiency [-].

The pumping power from the warm well is 0.45 kW and from the cold well 1.15 kW. The cold well requires greater pumping power, because the required volume is pumped during a shorter period of time, since the heating period is 243 days and cooling period only 122 days.

The existing heating system requires higher temperature level from the circulating water than the temperature obtained from the hot well. The heating system of the building is integrated with the AWHP and the maximum temperature of the circulating water is assumed to be 50 °C. The temperature of the extracted water is raised from the ATES temperature (5–15 °C) to the level of 50 °C by an integrated heat pump. Example configuration of the pump and the storage system is shown in Figure 16.

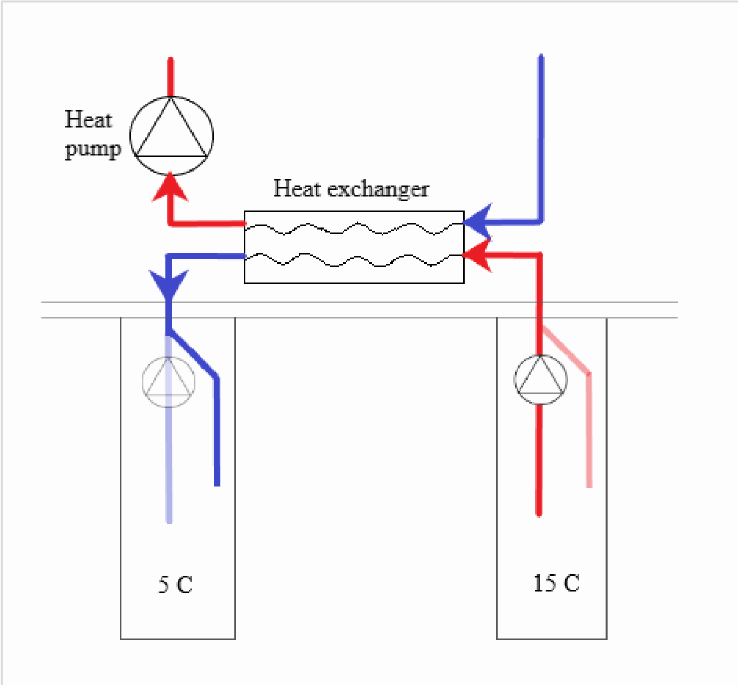


Figure 16. Flow chart from ATES combined with a heat pump in heating phase.

Peak heating and cooling power are approximated from the heating demand and temperature difference to determine the size of the heat pump. The peak power capacities are calculated as follows (Arola & Skorka-Niemi 2014, 1958)

$$P_{\mathrm{h,peak}} = \frac{Q \cdot \Delta T \cdot c_{\mathrm{v}}}{1 - \frac{1}{COP_{\mathrm{h}}}} \tag{23}$$

$$P_{\mathrm{c,peak}} = \frac{Q \cdot \Delta T \cdot c_{\mathrm{v}}}{1 + \frac{1}{COP_{\mathrm{c}}}} \tag{24}$$

where ΔT is the difference between inlet and outlet temperatures of the heat pump or heat exchanger [K].

The heat extraction temperature of the aquifer during the heating cycle is estimated followingly

$$\Delta T = \frac{E_{\mathrm{h}}}{c_{\mathrm{p}} \cdot m} = \frac{E_{\mathrm{h}}}{c_{\mathrm{v}} \cdot V_{\mathrm{h}}} \quad (25)$$

where c_{p} is the heat capacity of water [J/(kgK)]

m is the mass of water required for heating [kg]

c_{v} is the volumetric heat capacity of water [kWh/(m^{3}K)]

V_{h} is the volume of water required for heating [m^3].

The maximum peak heating power is obtained with the lowest hot well temperature, which cools down to 5.1 °C in the end of the heating season in May. The peak heating power is 138 kW, when the circulating water is calculated to reach the assumed maximum temperature level of the heating system.

During the cooling period the target room temperature of the building is assumed to be 18 °C and it is assumed to be the inlet temperature of the flow entering the heat exchanger. Extracted cold from the ATES cools the circulating water of the building and transfers heat from the building to the hot well. The maximum peak power for cooling is reached with the lowest cold well temperature, which is in the beginning of the cooling period 5 °C. The maximum peak cooling power is 117 kW.

4.2.3 Borehole Thermal Energy Storage

The additional input values for BTES calculations are the borehole diameter and spacing between boreholes. Typical drill diameters are 110–150 mm and the spacing is typically between 3–5 m, depending from the thermal properties of the ground. Nordell (1997, 173) has investigated the optimal borehole spacing and the optimal number of boreholes as a function of thermal conductivity of the storage material in an existing storage in Luleå (Figure 17.) The heat extraction and injection become easier as the thermal conductivity increases, which leads to increased optimal distance between boreholes and reduced number of boreholes. (Nordell 1997, 109-142)

(a) (b)

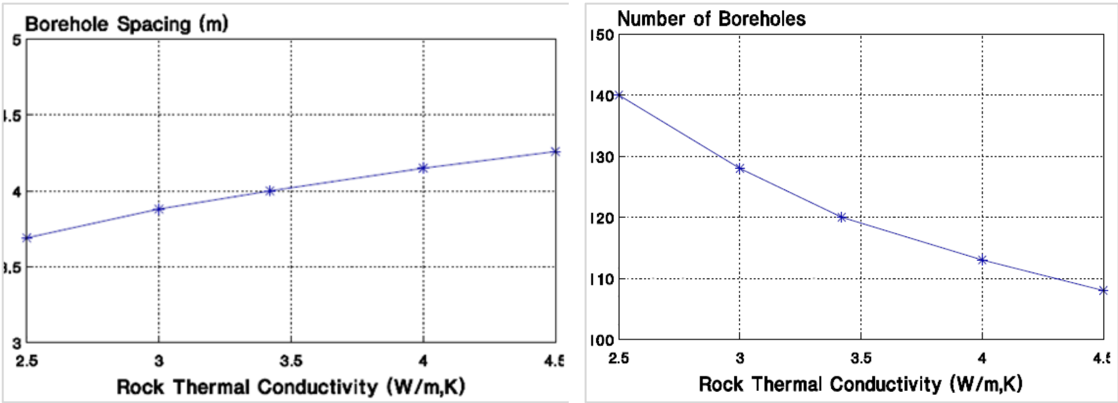


Figure 17. (a) Optimal borehole spacing and (b) optimal number of boreholes as a function of thermal conductivity of rock in existing BTES in Luleå. (Nordell 1997, 173.)

The thermal conductivity of the granite varies between 2.9–4.2 W/(mK) and the thermal conductivity of the ground is approximately 1 W/(mK) (Nordell 1997, 17–144). The spacing in rock BTES is approximated to be 4 m and the spacing in ground BTES 3.5 m with the drill diameter of 115 mm. The boreholes are drilled in the bedrock if the thickness of the soft surface layer is less than 30 m. If the thickness of the surface layer is more than 30 m the boreholes are drilled in the surface layer.

The cycle efficiencies of installed BTES vary mostly between 40–60 % (Rad & Fung 2016, 1554.) The heating volume is calculated from Equation 12 and the required volume is estimated with a storage efficiency of 50 %. The required charging energy is 369 MWh and it is assumed to be covered with heat from cooling and heat produced with the heat pump. The heated storage volume is 15 509 m^3 and required storage volume is 31 017 m^3 with the selected efficiency.

The boreholes are drilled in a hexagonal pattern and the diameter to height ratio is close to one for optimal A/V-ratio. The optimized depth and diameter of the storage are both 34 m and the horizontal surface area of the storage is 908 m^2. The diameter of one borehole installation is 3.56 m and the surface area 11.0 m^2. The number of boreholes is calculated from the storage and borehole area

$$n = \frac{A_s}{A_b} \tag{26}$$

where	n	is the number of boreholes [-]
	A_s	is the surface area of the storage [m^2]
	A_b	is the space of one borehole [m^2].

The number of boreholes is 83, hence, the total drilling is 2 835 m. The heating power provided by the heat pump is 7.91 kW. The drilling configuration of BTES is shown in Figure 18.

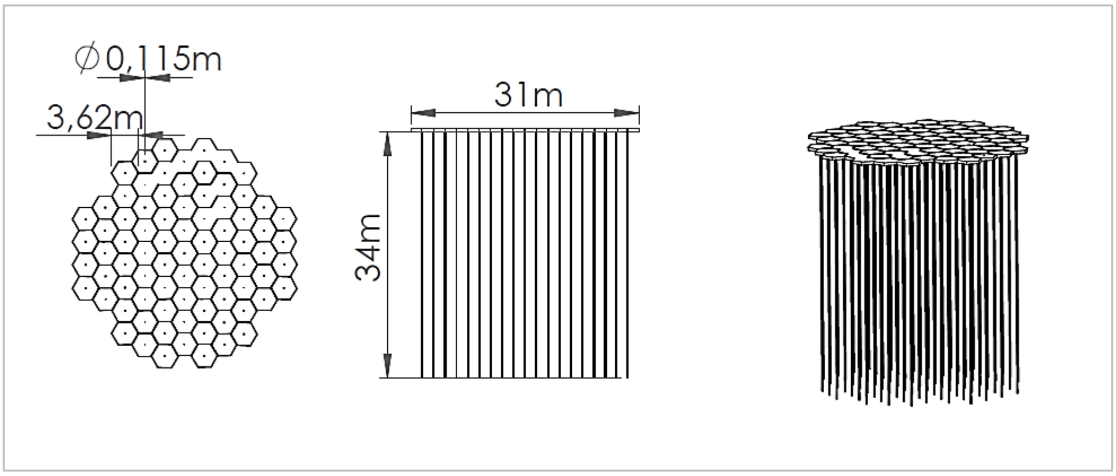


Figure 18. Schematic drawing from BTES system with 83 boreholes made in SolidWorks.

BTES systems are usually integrated with a buffer storage to balance the fluctuation between demand and supply, because the storage reacts slowly during charging and discharging. The required buffer volume is estimated from buffer to storage volume ratio in Drake Landing, Canada. With the ratio of 0.0071 l/m^3 and storage volume of 31 017 m^3, the volume of the integrated buffer storage is approximated to be 219 litres. (Kallesøe & Vangkilde-Pedersen 2019, 67–72)

4.2.4 Economic analysis

The main components of an ATES system are wells including submersible pumps, heat pump, piping and a heat exchanger to transfer heat and cold between ATES system and the heating system of the building. The drilling cost for wells is estimated from information obtained from a local contractor (Lappalainen 2020) and the drilling cost in the bedrock is approximately 28–33.3 €/m and an additional 66.6 €/m in the soft ground. The specific cost for submersible pumps is assumed to be 500 €/kW and for heat exchanger 35 €/kW (Todorov et al 2020, 12.) The heat pump cost is estimated from Haahtela & Kiiras (2012, 257) and is 290 €/kW in Lappeenranta and Imatra price area. The heat pump size optimized to cover the maximum heating demand.

The specific cost for drilling and heat pump cost for BTES are estimated with the same price estimations as for ATES. The heat pump is sized based on the average heating capacity and the buffer storage cost is assumed to be approximately 3.7 €/l (Danish Energy Agency 2018, 63). In addition, the pipes need to be excavated underground and the surface of the pipes is insulated. The excavation cost 3.5 €/m^3 is estimated from Haahtela & Kiiras (2012, 95) and calculated for 40 cm deep installation. The insulation cost is assumed to be 1.3 €/m^3 (Schmidt 2012, 10.)

The investment cost of the installation varies according to the location, size of the storage, storage material and the temperature difference of the storage. The drilling cost varies depending from the storage material and can be as much as three times more expensive in the soft ground layer than in the bedrock. The approximated investment cost for ATES and BTES system in Vuoksenniska case include an additional heat pump to raise the supply temperature to the system temperature. The cost of the storage system for ATES is shared in storage cost and heat pump cost.

The storage system is assumed to store the additional heat energy after AWHP installation during the heating season and the savings are calculated from alternative heat source, which in Vuoksenniska School is district heating. Savings in cooling are estimated from reduced electricity consumption when replacing a typical watercooler. The increase in electricity consumption and the use of AWHP for charging are reduced from annual savings. The estimated increased electricity consumption includes the consumption of the submersible pumps in ATES and the integrated heat pump for temperature raise. Table 13 shows the approximated investment costs for ATES and BTES. 10 % from the total investment costs is reserved for the project and is referred as other. The net savings for ATES and BTES storage systems are shown in Table 14.

Table 13. Approximated investment costs for ATES and BTES.

	ATES	BTES
Drilling, ground	9 752	283 265
Drilling, rock	-	-
Excavitation	-	1 274
Heat exchanger	4 106	-
Submersible pump	796	-
Heat pump	40 015	2 294
Insulation	-	102 355
Buffer storage	-	539
Other 10%	1 465	38 973
Total €	56 134	428 699

Table 14. Annual net savings in ATES and BTES.

	ATES	BTES
Savings, heating €	11 436	11 436
Savings, cooling €	2 590	2 590
Electricity, pumps €	-2 910	-3 879
AWHP charging €	-3 429	-6 327
Net €	7 687	3 819

Vanhoudt et al (2011, 3664) has reported the total investment cost for ATES system at Belgium Hospital Klina to be 579 €/kW but does not include the heating or cooling supply provided by heat pumps. Schmidt (2012, 10) has reported the construction cost from a 37 500 m^3 BTES system in Crailsheim to be 520 000 € resulting in a specific cost of 13.9 €/m^3. The difference between the approximated investment cost and calculated costs from four specific costs obtained from literature are plotted in Figure 19 for ATES and in Figure 20 for BTES.

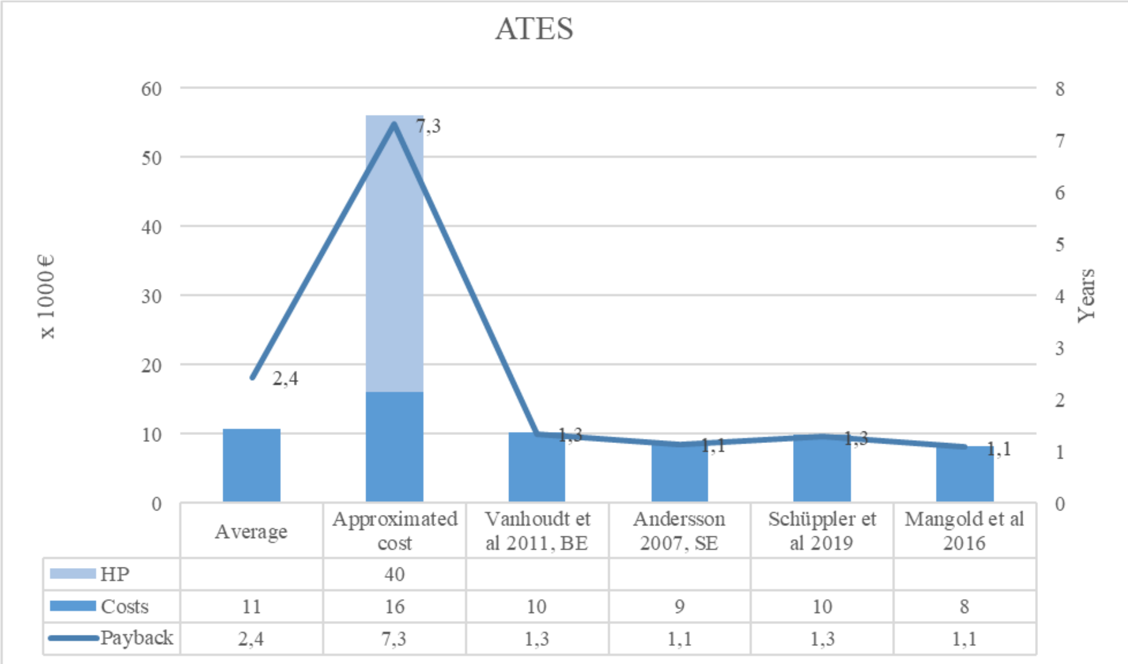


Figure 19. Approximated investment cost for ATES at Vuoksenniska compared with three other estimations with three specific costs.

As seen from Figure 19, the major share in the investment cost in ATES is the cost of the supporting heat pump. The heat pump is required, since the heating temperature in the existing real estate requires higher heating temperatures than the ATES alone can provide. Except from the heat pump, the approximated investment cost is aligned with the estimated specific cost from Schüppler et al in Germany and the specific cost of Mangold et al, but also with the realized cost of the Belgium hospital (Vanhoudt et al 2011, 3664) and realized cost of ATES in Malmö (Andersson 2007, 235)

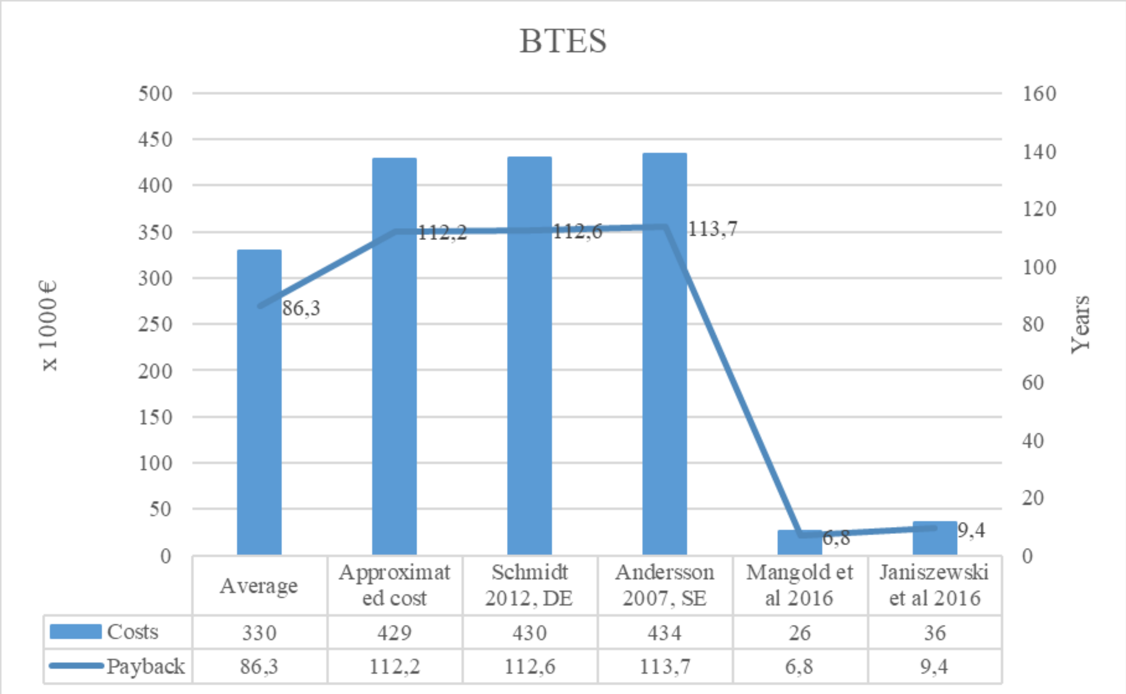


Figure 20. Approximated investment cost for BTES at Vuoksenniska compared with three other estimations with three specific costs.

As shown in Figure 20, the specific cost of a borehole installation varies according to the source. Although, the price approximation is in line with the estimations made based on the specific cost of realised BTES systems. The specific costs from Mangold et al (2016, 8) and Janiszewski et al (2016, 7) are estimations based on their studies and the difference may explained with the economy of scale in these estimations. The results for both storage types are compared in Table 15. Payback periods with estimated and average investment cost from

Table 15. Payback periods with estimated and average investment cost from literature and approximation.

	ATES	BTES
Approximated investment cost, €	56 134	428 699
Payback with approximated cost, a	7.3	112.2
Average investment costs, €	10 677	329 717
Payback with average investment cost, a	2.4	86.3

From Table 15. can be concluded, that the ATES system is found economically potential despite the increase in cost caused by the integrated heat pump. The payback period of ATES is approximated to be 7.3 years. The BTES installation is not found potential within the maximum payback period of 15 years. The high cost and low profits of the application are explained with high drilling cost in the soft ground and high electricity consumption due heat production with AWHP.

4.3 Case 2: School of Eastern Finland

School of Eastern Finland is a case real estate in Lappeenranta, which locates at borehole restriction area. The existing aquifer at the case real estate is classified as an important water resource and cannot be utilised as thermal energy storage. Therefore, the possible storage applications in the study are limited to pit and tank thermal energy storages.

The case real estate is built in 2006 and the total heating area is 2 138 m^3, which is heated with district heating. The additional heat demand after AWHP installation and window replacement is simulated to be relatively small and less than half from cooling demand, so no other heat source is required. The estimated energy demand of the case building after before mentioned energy efficiency improvements are presented in Figure 21. As in Vuoksenniska School, also here the theoretical cooling demand is estimated with the assumption of no heat load from humans and appliances during summer vacation in June and July (Imatra n.d. b.)

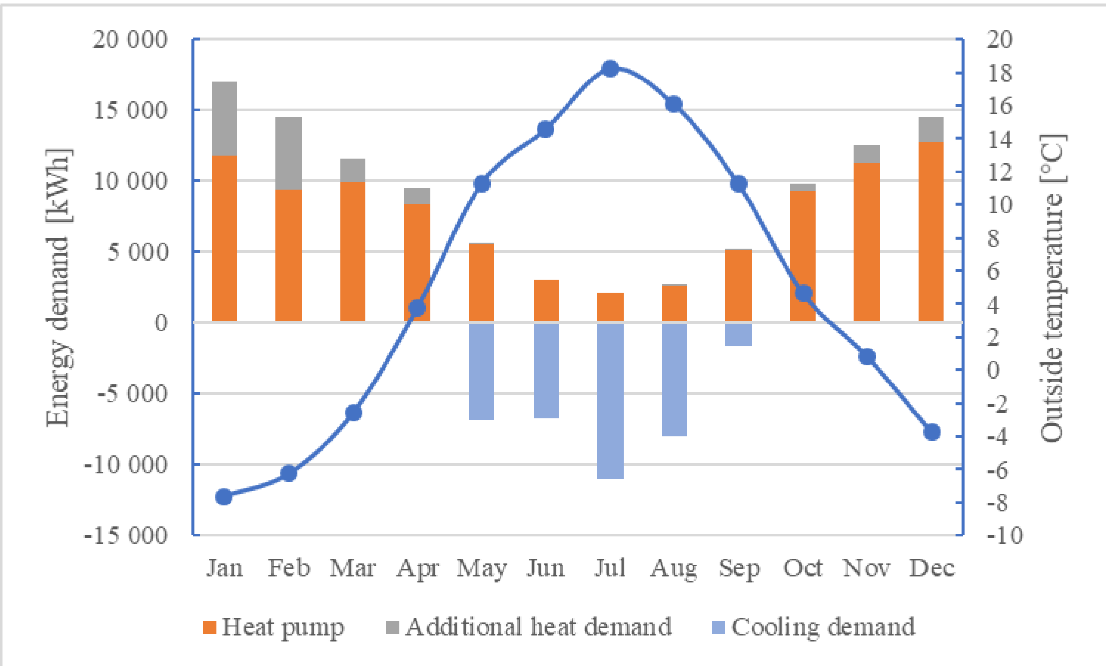


Figure 21. Monthly energy demand and outside temperature of School of Eastern Finland. Data: *Public-Private Partnership in real estate energy efficiency improvements and finance* –project; Finnish Meteorological Institute 2019.

4.3.1 Input values

The input values for Excel-tool are the geological conditions obtained from Table 4 and the energy costs for district heating and electricity. Electricity cost is approximated similarly as in Vuoksenniska School case. The calculative maximum flow rate is approximated within the *Public-Private Partnership in real estate energy efficiency improvements and finance* –project to be 0.48 m^3/h and the local district heating to be 83.12 €/MWh and 67.03 €/MWh without VAT. PTES and TTES applications are calculated as high temperature storages, so no heat pump is required to raise the supply temperature. The cooling machine is assumed to be a simple watercooler with COP of 2.7.

4.3.2 Pit Thermal Energy Storage

The overall efficiency for PTES is 70 % (Danish Energy Agency 2018, 50.) The required volume for heating is calculated with Equation 12 and the required storage volume is calculated with overall efficiency. The required storage volume in the case real estate is 683 m^3.

The storage geometry is chosen to be a truncated cone with circular cross section, which is buried in the ground. Additional values for geometry are the bottom radius and height, including maximum depth. The soil depth at the site limits the maximum depth of the pit, here 10 m. The height and bottom radius need to be modified to optimize the geometry with minimum A/V-ratio. The slope dimension for shallow pit is chosen to be 30 ° (Ochs 2019.) The geometry of the storage is shown in Figure 22.

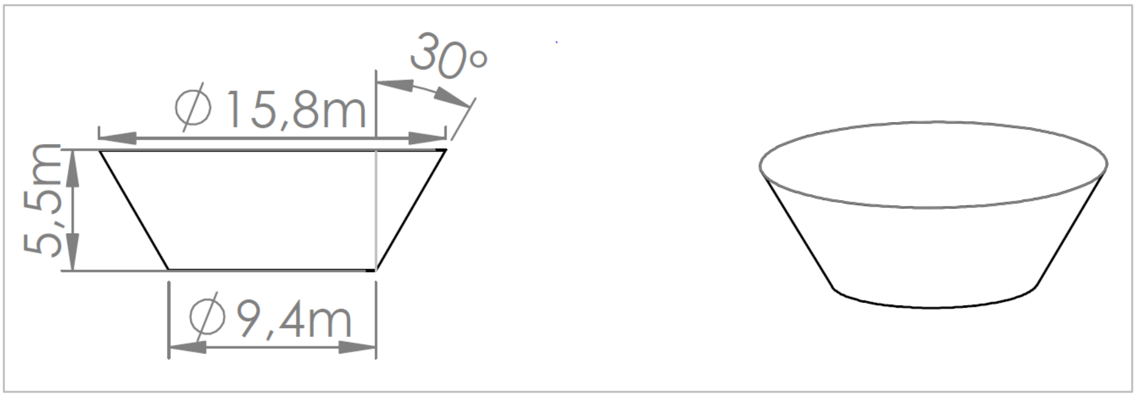


Figure 22. Geometry of the pit storage made in SolidWorks.

With bottom radius of 4.7 m and depth of 5.5 m the storage volume is 698 m^3, which is slightly over the required storage volume. The top diameter of the storage is 15.75 m and the bottom diameter is 9.40 m. The A/V-ratio of the storage is 0.74.

4.3.3 Tank Thermal Energy Storage

The overall efficiency for TTES is approximated to be 98 % (Danish Energy Agency 2018, 59.) The required volume for heating is calculated with Equation 8 and the required storage volume is calculated with overall efficiency. The required storage volume for the case real estate is 488 m^3.

The storage geometry is chosen to be a cylinder, which is either above, partly or fully in the ground. The side view of the cylinder is shown in Figure 23. Additional value for geometry is height. The soil depth at the site limits the maximum depth of the tank, when buried. The height and bottom radius need to be modified to optimize the geometry with minimum A/V-ratio. In this tool, the tank is on the ground and possible excavation work is not considered in the economic analysis of TTES. With the height of 10 m, the diameter of the cylinder is 26 m and the A/V-ratio is 0.70.

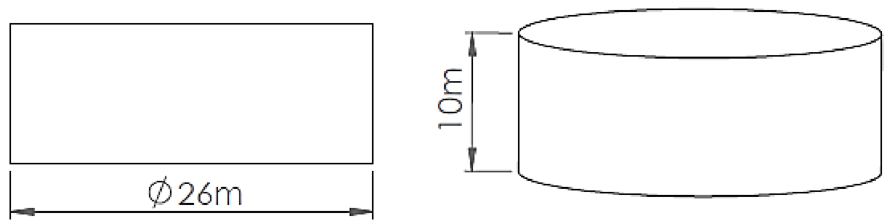


Figure 23. Geometry of the tank storage made in SolidWorks.

4.3.4 Economic analysis

The main components for PTES and TTES systems filled with water are insulation and the stratification device for charging and discharging. Also, a draining and a floating cover are considered for PTES, as well as a control system. In TTES, the major shares of total cost are construction and stainless-steel liner.

Typical values for price approximation of the pit storage are obtained from the specific cost of Sunstore 2, which has a total storage volume of 10 000 m^3 (IEA DHC 2018, 76.)

Typical values for tank storage price estimation are taken from specific cost of buried TTES installed in Munich, Germany, which has a total storage volume of 5 700 m^3 (Schmidt 2008.) The approximated investment costs for PTES and TTES are listed in Table 16.

The annual saving savings are from alternative heat source and from cooling. The savings from cooling are estimated from reduced electricity consumption when replacing a typical watercooler. Since PTES and TTES applications are calculated as high temperature storages, the heat can be directly utilized for space heating. In School of Eastern Finland the cooling energy is sufficient for charging and there is no increase in electricity consumption. The annual net savings for both storage applications are listed in Table 17.

Table 16. Approximated investment costs for PTES and TTES.

	PTES	TTES
Construction	-	31 008
Ground work	5 302	9 792
Charging/discharging device	1 884	10 608
Insulation	1 256	10 608
Draining	209	-
Cover	10 604	-
Stainless steel liner	-	21 216
Control system	558	-
Other PTES 10%, TTES 3%	2 023	2 497
Total €	21 836	85 730

Table 17. Annual net savings in PTES and TTES.

	PTES	TTES
Savings, heating €	1 135	1 135
Savings, cooling €	753	538
Electricity consumption €	-	-
Net €	1 888	1 673

The payback period and average payback period are calculated from the approximated investment cost and from the average of estimated cost using specific costs from literature. The results and differences in costs and payback periods are listed in Table 18. The difference between price estimations from literature and the approximated investment cost are shown in Figure 24 for PTES and in Figure 25 for TTES.

Table 18. Payback periods with approximated and average investment cost from literature and approximation.

	PTES	TTES
Approximated investment cost, €	21 836	85 730
Payback with approximated cost, a	11.5	51.2
Average investment costs, €	27 599	76 144
Payback with average investment cost, a	14.6	45.5

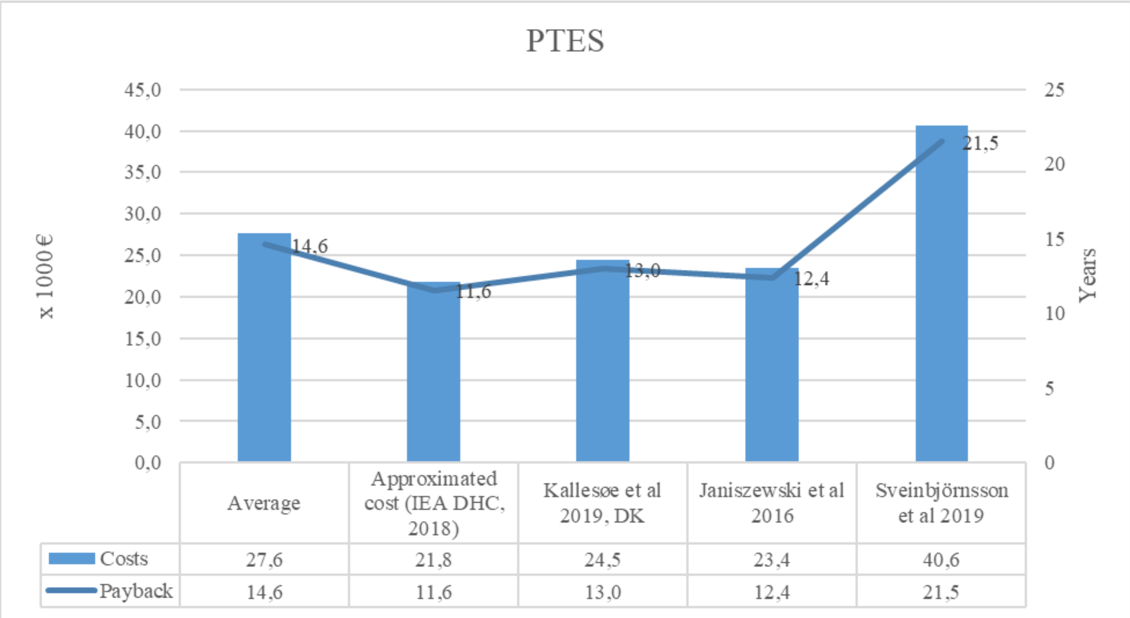
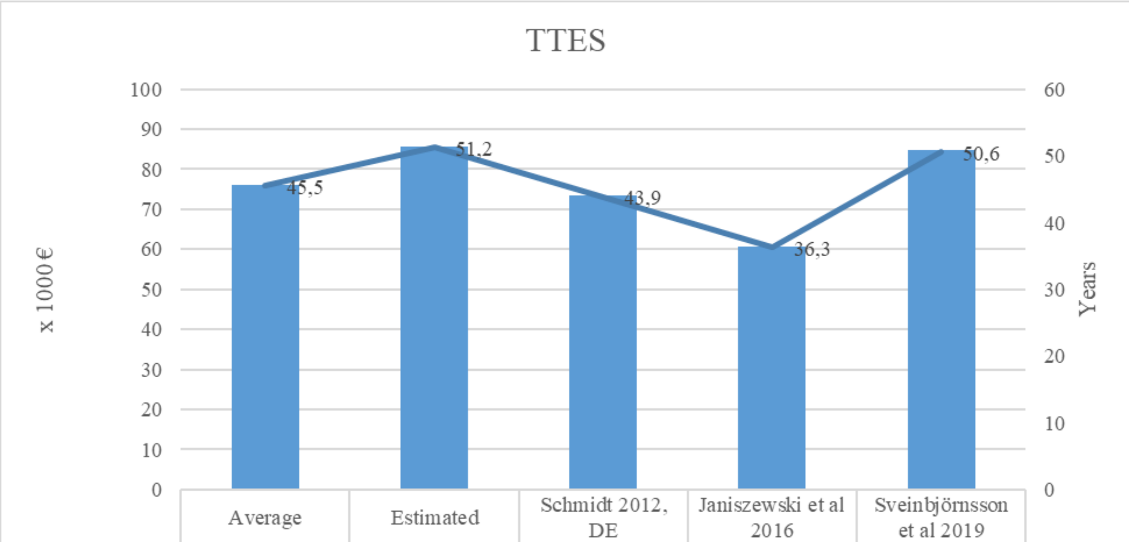


Figure 24. Approximated investment cost for PTES at School of Eastern Finland compared with three other estimations with three specific costs.



	Average	Estimated	Schmidt 2012, DE	Janiszewski et al 2016	Sveinbjörnsson et al 2019
Costs	76	86	73	61	85
Payback	45,5	51,2	43,9	36,3	50,6

Figure 25. Approximated investment cost for TTES at School of Eastern Finland compared with three other estimations with three specific costs.

As seen from the figures, the different cost estimations are within the same price level as the approximated investment costs. The thermal capacity and the geometry of the storage do not depend on the ground properties at the construction site, so the location does not have a strong impact on storage costs.

5 RESULTS AND COMPARISON

5.1 Vuoksenniska School and School of Eastern Finland

In the first case, the payback period and the specific cost are lowest in ATES due to low investment costs. If the aquifer is not utilisable for storage purposes, the choice is between PTES and TTES applications.

The soft ground layer at the case real estate is deep and the boreholes should be drilled in the gravel layer. Drilling in the ground is more expensive than drilling in the rock, which increases the specific costs of the storage. In addition, the volumetric heat capacity of the gravel is lower than granite's and the usable temperature difference changes from 45 K to 20 K in ground based BTES. Also, due to lower efficiency, more charging energy need to be produced for BTES, which reduces the annual profitability of the storage system.

These features increase the required storage volume and decrease the profitability of the technology compared to School of Eastern Finland, where boreholes would be drilled in the bedrock and cooling energy is enough for charging. Eventually the specific cost of PTES is not much higher than in BTES and with higher yearly savings, the payback period results lower than in BTES. The approximated investment cost, specific cost and payback period of each application are compared in Table 19.

Table 19. Case Vuoksenniska School: Approximated costs and payback periods for storage types.

	ATES	BTES	PTES	TTES
Investment cost [€]	56 134	428 699	234 533	806 760
Savings [€/a]	7 687	3 819	10 032	11 699
Specific cost [€/kWh]	0.3	2.3	1.3	4.4
Payback [a]	4.7	112.2	23.4	69.0

In the second case, School of Eastern Finland, the relevant applications are PTES and TTES, where investment cost of PTES is less than half of TTES. The stored energy at the case real estate is relatively low compared to other cases, so the required storage volume is relatively small, and the payback period of the storage option is moderate. However, if drilling at the case real estate would not be restricted and BTES option would be applicable, it would be most cost-effective storage option (Table 20).

Table 20. Case School of Eastern Finland. Average costs and payback periods for storage types.

	ATES	BTES	PTES	TTES
Investment costs [€]	-	(7 048)	21 836	85 730
Savings [€/a]	-	(1 834)	1 888	1 673
Specific cost [€/MWh]	-	(0.4)	1.3	5.1
Payback [a]	-	(3.8)	11.6	51.2

5.2 Results

The recommended storage type for selected case real estate is calculated to cover the additional heat demand after energy efficiency improvements. The temperature level of the system is assumed to be the inlet temperature of the radiators, here 50 °C, and the return temperature to be same with the estimated room temperature of 18 °C. The heat capacity of the storage is calculated for monthly heat demand with the assumption, that the required heat energy is covered during the cooling period.

Thermal storages are dimensioned for ATES, BTES, PTES and TTES systems, when applicable. The storage geometry is chosen to be a truncated cone for PTES and a vertical cylinder for TTES. The costs are approximated as described in the previous chapter. The profitability is calculated from estimated savings in heating and cooling and the choice of the application is based on the shortest payback period. The recommended storage type, investment cost, savings and payback time with additional comments are listed in Table 21 for Lappeenranta case real estates and in Table 22 for Imatra case real estates.

Table 21. Recommendations for Lappeenranta case real estates.

Lappeenranta	Storage type	Investment cost [€]	Savings [€/a]	Payback [a]	Additional
1. City Hall	-	-	-	-	Short term storage tank
2. Library	-	-	-	-	Short term storage tank
3. School of Eastern Finland	PTES	21 800	1 900	11.6	-
4. Tupatallinkatu	(PTES)	(47 200)	(1 300)	(39.2)	Not profitable with AWHP heat source
5. Höyläkatu	BTES	38 100	3 000	12.6	.

Table 22. Recommendation for Imatra case real estates.

Imatra	Storage type	Investment cost [€]	Savings [€/a]	Payback [a]	Additional
1. City Hall	BTES	71 000	19 800	3.6	-
2. Cultural Center Virta	BTES	61 704	18 800	3.3	-
3. Vuoksenniska School	ATES	56 800	7 200	7.9	-
4. Mansikkala	(BTES	(145 100)	(7 600)	(19.1)	Not profitable with AWHP heat source
5. Tietotalo	-	-	-	-	Short term storage tank
6. Kosken linkki	-	-	-	-	Short term storage tank
7. Koskikeskus	-	-	-	-	Short term storage tank

As seen from the tables, technically feasible storage type was found in two out of five cases in Lappeenranta and in four out of seven cases in Imatra. Except for Mansikkala and Tupatallinkatu cases, the storages were found economically potential within the maximum payback period of 15 years. The most potential storage type was BTES in four out of six cases, when the geological conditions were favourable and energy from cooling was enough to cover most of the heat required for charging.

6 DISCUSSION

The goal of the study was to compare feasible seasonal storage options for case real estates of *Public-Private Partnership in real estate energy efficiency improvements and finance* –project and find the most techno-economically potential seasonal storage option from chosen storage types to supply an additional heat source. The calculations were based on collected and calculated data from previous studies made for the project. The scope of this study was limited to economically and technically feasible storage types, which were chosen to be aquifer, borehole, pit and tank thermal energy storages. By selecting the right alternative to the system and designing it correctly, seasonal storage system can be implemented successfully and profitably.

Based on the research made in this study, thermal energy storages were found technically feasible, when there were no areal or size restrictive factors. The storage applications were considered economically feasible, if the payback period of the storage system was less than 15 years. The study found technically feasible seasonal storage system for seven out of 12 cases, from which five out of seven were found economically potential within maximum payback period of 15 years. Five out of 12 case real estates had space limitations because of the central location at the city or lacked in available land area. A suitable seasonal storage type for these case real estates was not found inside the scope of the study, because the studied applications required large storage volumes for covering the additional heat demand of the real estate. However, a short-term storage, PCM or TCES, could be applied in the real estates, but were not investigated further in this study.

The capacity and size of a short-term storage are smaller, so a moderate hot water tank could potentially be fitted in the technical room of the real estate. Nevertheless, the technical feasibility and economic potential of a short-term storage would require additional investigations. PCM and TCES storages on the other hand require less space, because of high energy density of the storage material. Still, the storage cost of PCM and TCES are high and therefore would probably not be economically potential in these case real estates.

The storage calculations were run to cover the additional heat demand after AWHP installation and improvements in insulation and ventilation. After techno-economic analysis made with Knuutila's (2019) Excel-tool, the suggested heat pump for most of the case real estates is AWHP and for the rest GSHP. The GSHP can be operated in lower outside temperatures, which reduces the demand for additional heat source resulting smaller storage sizes. The GSHP installation may affect the performance and design of TES, which should be considered when applying underground storage systems with GSHP and is therefore not included in this study. The same initial conditions were chosen for all case real estates, so the results of the study are more comparable with one another. The information on final investment decisions is also not been made at the time present and therefore the information on forthcoming installations was not available.

The heat demand calculations were based on simulated data and theoretical cooling demand of the building was approximated based on the heat loads and losses. To discover the deficiency of the theoretical approach in cooling demand, an hourly based calculation was run with constant indoor temperature for one case building. The simulation resulted 18 % lower cooling demand for the reference year than the simulation based on hourly simulation. The savings from cooling decreased by 3.8 %. In BTES the electricity consumption of the heat pumps increased 9.8 % and total profitability was 4.5 % lower. In PTES and TTES was found no difference, because cooling capacity of the storage types were met in both calculations. The difference in cooling demand led to two months shorter payback time in BTES system and had no effect in PTES or TTES. The inaccuracy in the cooling calculations was found acceptable in the scope of this study, since the economical difference between the calculation methods did not cause significant changes in the results and did not affect in the chosen storage recommendation.

In the Excel-tool the heat for charging was assumed to be primarily obtained from cooling energy and secondarily from AWHP heat production. Using AWHP for charging reduces the annual savings due increase of purchased electricity. Figure 26 compares the annual savings versus expenses in borehole storage application in three real estates with diverse cooling and heating characteristics resulting different net savings.

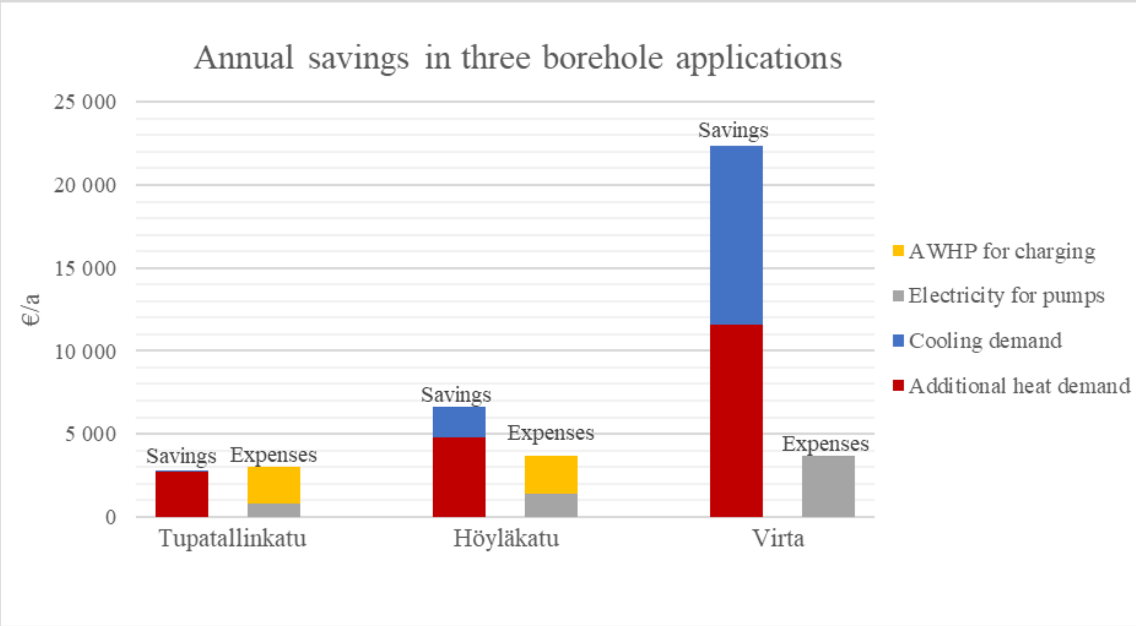


Figure 26. Annual savings of BTES in three case real estates.

As seen from the figure, the economic potential of the application is strongly affected by the additional heat demand and cooling profile. In the case real estates with higher cooling demand compared to additional heat demand, the storage system applications were found more profitable. If the heat energy from cooling demand is sufficient to cover the energy required for charging, there is no need or only a low need for additional heat production via other heat source.

The required charging energy depends also from the storage cycle efficiency requiring more heat energy in lower efficiencies. The cycle efficiencies of TES systems vary greatly especially in sensible heat storage systems from 50 to 90 % as seen in Chapter 2.1. The efficiency of the storage depends from several factors such as the storage type, temperature level and local conditions. Large storage systems benefit from economies of scale. Larger storages have lower A/V-ratios, which reduces heat losses relative to volume and so the heat losses decrease as the size increases. The cycle efficiency for each storage system in the Excel tool is approximated from reported efficiencies of operating storage systems in Europe and Canada. The efficiency of the realized storage system may differ from the efficiencies chosen due to location, operating conditions and size.

The Excel tool compares selected storage types by analyzing the investment costs, profitability and the payback period of each alternative. The economic analysis is based on the reported costs of existing plants and the estimated investment costs based on reported unit costs and information on local unit costs. The investment costs of the existing and calculated pilot plants in Germany and Denmark are collected and the specific investment costs of large-scale seasonal storages are compared in water equivalents in Figure 27.

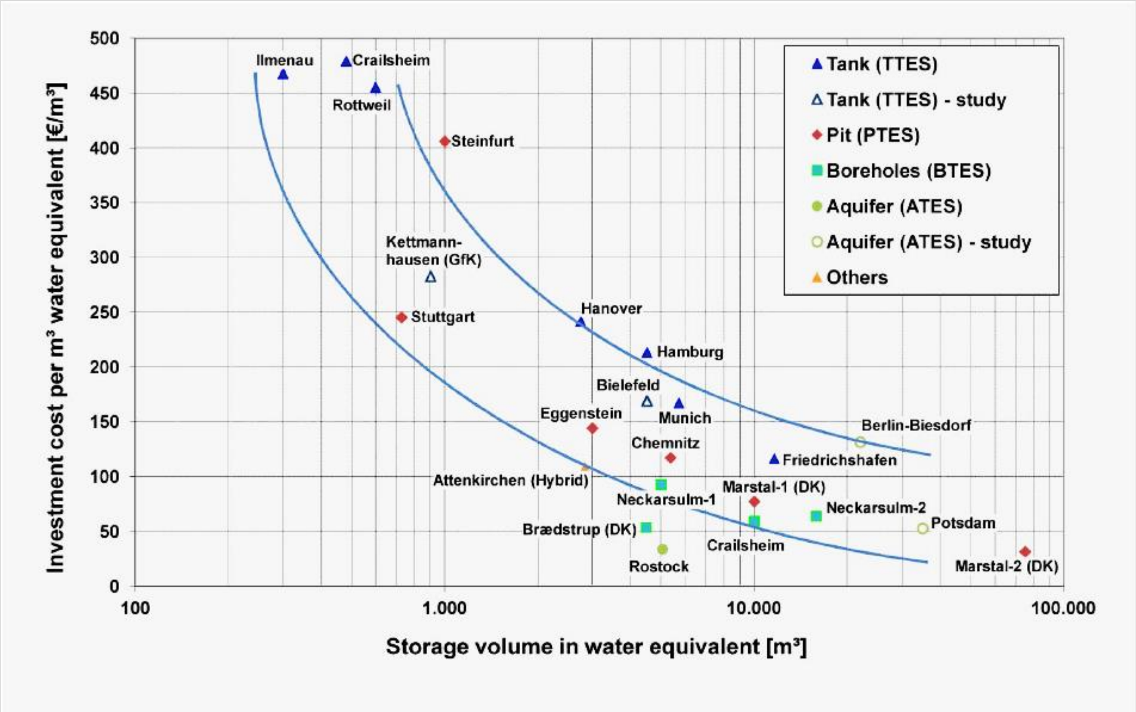


Figure 27. Specific costs of large-scale seasonal storages, excluding planning costs and VAT. (Mangold et al 2016, 43.)

The investment costs were compared using the average specific cost of four price estimates. From the figure can be noticed, that the lowest investment costs for a storage type of the same capacity is in ATES and the second lowest in BTES. The highest specific costs are in TTES over PTES, but in small scale systems PTES and TTES seem more commonly applied.

The specific costs of BTES systems fluctuated the most between specific costs from literature, ranging from 2 500 €/MWh in Flexynets (Sveinbjörnsson et al 2019, 26) to 10–

140 €/MWh in Guideline for Seasonal Thermal Energy Storage Systems in the Built Environment (Mangold et al 2016, 8.) For other storage types the reported costs were more uniform. Janiszewski et al (2016) have studied the feasibility of underground seasonal storage for solar collector system in Finland and have estimated the specific costs for preliminary-sized solar community in Finland. The *Solar Community Concept* investigated in the study is a community with total heat demand of 288 MWh/a. In the study Janiszewski et al evaluated the investment costs of BTES, TTES, CTES (*Cavern thermal energy storage*) and PTES, where BTES had the lowest specific investment costs per water equivalent (10 €/m^3). The specific costs for other storage types from lowest to highest were PTES 49 €/m^3, CTES 80 €/m^3 and TTES 127 €/m^3.

After techno-economic analysis of ATES, BTES, PTES and TTES storages, ATES turned out the most cost-effective storage type in Vuoksenniska School, where all storage types were found technically applicable. In the cost estimation, drilling costs were 66 % of the total cost in BTES applied in the soft ground layer at Vuoksenniska School in contrast to 16 % of the total cost in ATES. The difference is explained with the number of boreholes required, which was two for ATES and 83 for BTES. In School of Eastern Finland, the drilling cost would be 43 % of the total cost, if applicable. The drilling cost in rock based BTES are lower due to better thermal capacity of the rock and less expensive drilling per meter.

The most economically potential storage type for other case buildings was BTES, except in School of Eastern Finland, where the payback time of PTES ended up shorter. Better storage efficiency of water filled storage application results to less use of AWHP for charging and due to thick soft ground layer and expensive drilling, PTES came more profitable. In contrast to higher investment costs, PTES and TTES systems achieve higher annual savings. Also, no assisting heat pump was assumed to be required to raise the supply temperature in high temperature applications. From water filled storages PTES was found more profitable due higher construction cost of TTES.

In Tupatallinkatu case no storage system integrated with AWHP was found profitable, because the cooling demand of the real estate covered only 8 % of the additional heat demand. The rest of the charging energy would need to be produced with AWHP, which resulted in low annual savings due to extensive electricity consumption. The best storage option at Tupatallinkatu would be PTES with a payback period over 39 years with the current integration.

The Excel-tool was developed to compare chosen storage options and does not give accurate models for thermal energy storage integration. The tool provides an approximation of costs and savings achieved with each storage type comparing the economic potential of the storage types. The tool can also be used for real estates outside the project, when the energy consumption and hydrogeological conditions are known. For more accurate calculations the real cooling demand of the building should be known and the economic potential of other heat sources for charging should be estimated. Also, more information from system requirements and the hydrogeological conditions at the case real estates needs to be collected, so more accurate cost estimations can be made.

In further studies, the size of the assisting heat pump and the reliability to cover the peak heat demand could be estimated more accurately with daily or hourly simulation. The integration with the existing heat pump should also be investigated more detailed, because the storage application may affect on the size requirement of the heat pump.

The storage system needs be designed according to the system demands and meet the system supply and return temperatures, when it is applied in an existing building or designed in a new one. In an old building the heating is usually transferred via plate radiators with high temperature of the circulating fluid. Therefore, for low temperate ATES and BTES systems the temperature level needs to be raised to the system level. For further studies, the economic potential of high temperate ATES and BTES could be investigated. The high temperature applications could be integrated in the system without an assisting heat pump, but the high temperature level could lead to increased thermal losses and require more heat for charging.

Another study topic could be the integration of two storage systems. The hybrid system could use the short-term storage as a buffer to balance fluctuation in heating and cooling demand. Moreover, the short-term storage could store surplus electricity from the PV panels or from the grid as sensible heat. If electricity is used for heat production of the real estate, the storage can also be used to shift energy purchase to low cost periods.

7 CONCULSIONS

Underground thermal energy storages can be considered as relevant storage applications for public real estates in northern conditions and can be found economically potential with a suitable location and cooling and heating profile of the real estate. Thermal energy from summer can be stored for winter and be utilized as an additional heat source cost-effectively in cases, where the cooling demand can nearly or fully cover the required heating capacity and the geological conditions are favorable for the storage application.

Selected technologies were found applicable in seven out of 12 cases, from which five out of seven were economically potential with a payback period less than 15 years. From the studied storage technologies, aquifer thermal energy storage was the most economically potential in the case were all storage types were found applicable. In four out of seven cases the investment costs of BTES were the lowest with the shortest payback periods. In one case the payback time in PTES ended up shorter than in BTES due to high drilling cost in soft ground material and higher storage efficiency of PTES leading to higher annual savings. In the case of drilling restrictions existed, PTES was found more profitable than TTES.

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