Underground Thermal Energy Storage (UTES)

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My introduction

- Post-doctoral researcher at Aalto University and Rock Mechanics Specialist at Fractuscan Ltd
- Academic background:
  - DSc in Geoengineering @ Aalto, 2019
  - Master’s in Mining Engineering (EMC European Mining Course) @ Aalto, TU Delft & RWTH Aachen, 2014)
- Research topics: underground thermal energy storage, fracturing geomechanics, photogrammetry, virtual reality, risk assessment

Learning goals

After this session, you should

- be able to differentiate between different UTES methods
- be able to describe the typical phases of UTES projects
- be able to tell why do we need site investigation in UTES projects
- how do we measure thermal properties of rocks relevant for UTES

Content

1

UTES methods

2

UTES project

3

Thermal properties of rocks and soils

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Content

1

2

3

UTES methods

UTES project

Thermal properties of rocks and soils

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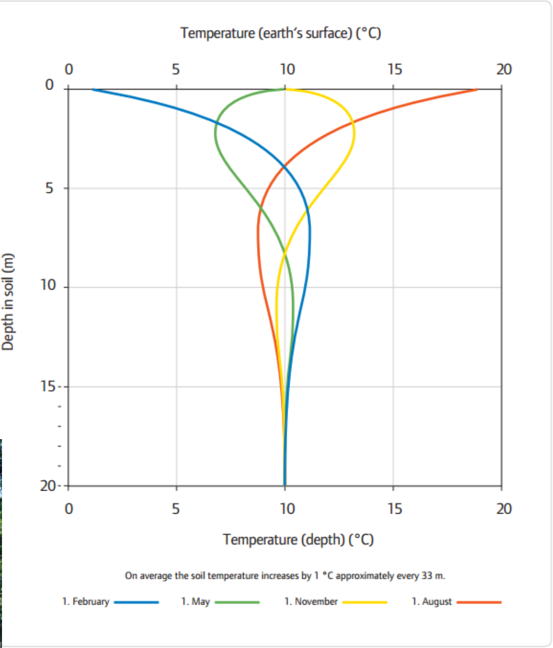
Why do we need to store thermal energy?

- Intermittent nature of renewable energy
- Supply and demand mismatch
- Passive energy storage since early humans

Passive energy storage in ground

flickr.com

hankahomesteadmuseum.org



https://web.uponor.hk/

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What are the requirements for a sensible heat storage medium?

LOW COST AND HIGH UTILIZATION RATE SYSTEM (LOW PAYBACK PERIOD)

HIGH ENERGY STORAGE DENSITY AND THERMAL EFFICIENCY

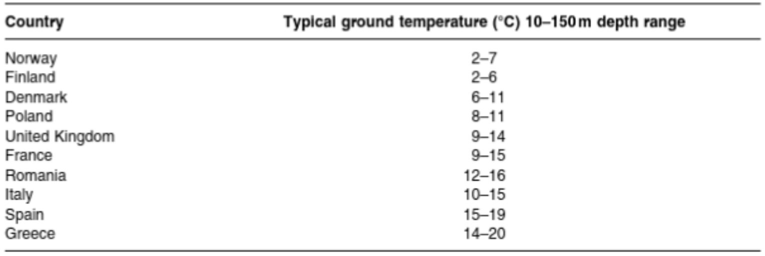
ENVIRONMENTAL COMPATIBILITY

WATER

ROCK/SOIL

The ground as a heat storage reservoir

- **High heat capacity**
    - Water ≈ 2*rocks
- **Moderate thermal conductivity**
    - Rocks 2 – 3 W $m^{-1}K^{-1}$
        - Depends on the mineral composition
    - Soils 1 – 2 W $m^{-1}K^{-1}$
        - depends on water content



Country	Typical ground temperature (°C) 10–150 m depth range
Norway	2–7
Finland	2–6
Denmark	6–11
Poland	8–11
United Kingdom	9–14
France	9–15
Romania	12–16
Italy	10–15
Spain	15–19
Greece	14–20

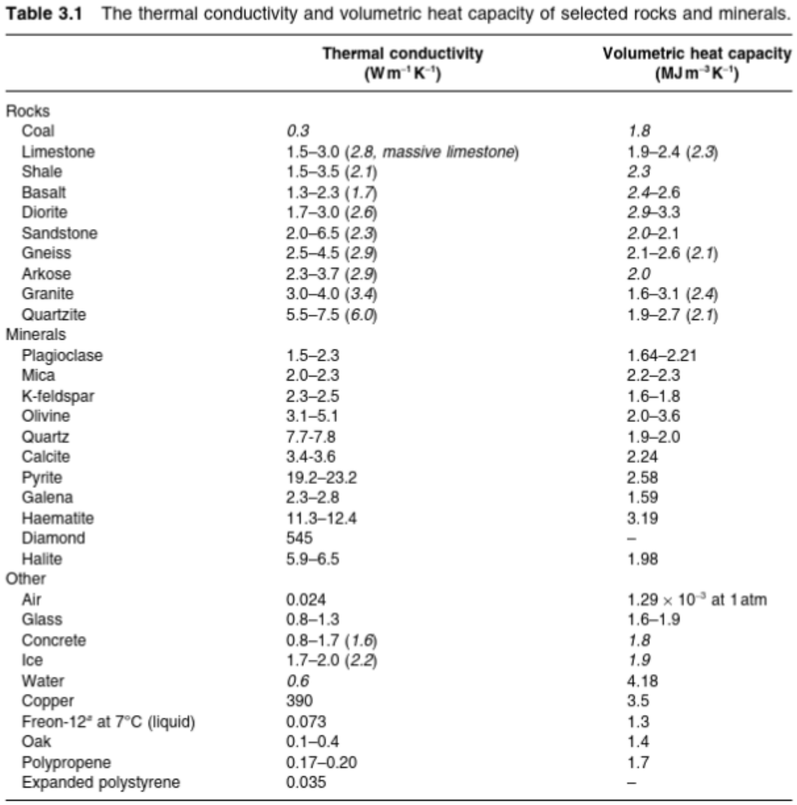


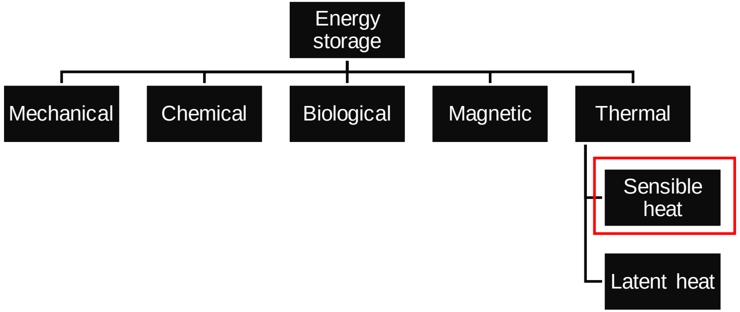
Table 3.1 The thermal conductivity and volumetric heat capacity of selected rocks and minerals.

	Thermal conductivity ($W m^{-1} K^{-1}$)	Volumetric heat capacity ($MJ m^{-3} K^{-1}$)
Rocks		
Coal	*0.3*	*1.8*
Limestone	1.5–3.0 (*2.8, massive limestone*)	1.9–2.4 (*2.3*)
Shale	1.5–3.5 (*2.1*)	*2.3*
Basalt	1.3–2.3 (*1.7*)	*2.4*–2.6
Diorite	1.7–3.0 (*2.6*)	*2.9*–3.3
Sandstone	2.0–6.5 (*2.3*)	*2.0*–2.1
Gneiss	2.5–4.5 (*2.9*)	2.1–2.6 (*2.1*)
Arkose	2.3–3.7 (*2.9*)	*2.0*
Granite	3.0–4.0 (*3.4*)	1.6–3.1 (*2.4*)
Quartzite	5.5–7.5 (*6.0*)	1.9–2.7 (*2.1*)
Minerals		
Plagioclase	1.5–2.3	1.64–2.21
Mica	2.0–2.3	2.2–2.3
K-feldspar	2.3–2.5	1.6–1.8
Olivine	3.1–5.1	2.0–3.6
Quartz	7.7-7.8	1.9–2.0
Calcite	3.4-3.6	2.24
Pyrite	19.2–23.2	2.58
Galena	2.3–2.8	1.59
Haematite	11.3–12.4	3.19
Diamond	545	–
Halite	5.9–6.5	1.98
Other		
Air	0.024	1.29×10^{-3} at 1 atm
Glass	0.8–1.3	1.6–1.9
Concrete	0.8–1.7 (*1.6*)	*1.8*
Ice	1.7–2.0 (*2.2*)	*1.9*
Water	*0.6*	4.18
Copper	390	3.5
Freon-12[a] at 7°C (liquid)	0.073	1.3
Oak	0.1–0.4	1.4
Polypropene	0.17–0.20	1.7
Expanded polystyrene	0.035	–

Banks, 2012

UTES

UTES = “systems for storing thermal energy using natural underground sites” (Lee, 2013)


Energy storage

Mechanical
Chemical
Biological
Magnetic
Thermal

Sensible heat
Latent heat

- Developed since 1970
- used when large storage volumes are needed
- Temperature: Low vs high temperature
- Purpose: heating, cooling, combined heating and cooling
- Technology: boreholes, aquifers, caverns, pits
- Application: residential, commercial, industrial

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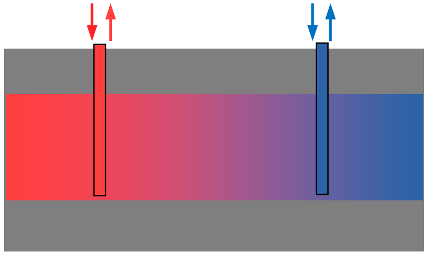
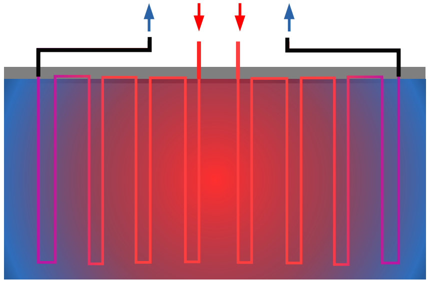
UTES methods

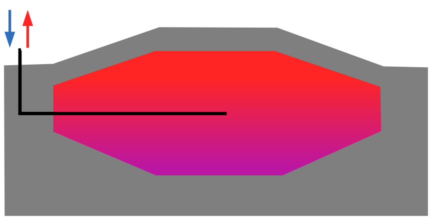
- Most common in aquifers (ATES) and boreholes (BTES)
- Other: caverns (CTES), pit (PTES) and tank (TTES), Combi/hybrid
- Depends on site specific conditions
  - Geology (rock vs. soil, properties)
  - Groundwater
- Engineering challenges:
  - Selecting the best UTES method
  - Selecting the most efficient shape
  - Economical excavation



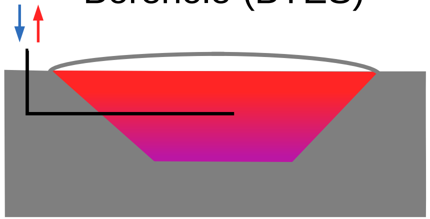
Aquifer (ATES)



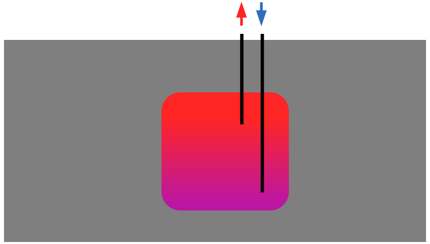
Borehole (BTES)



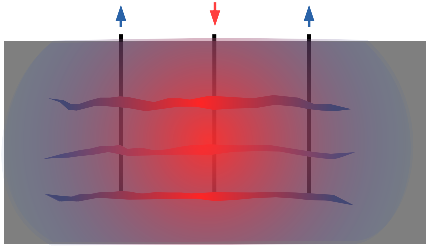
Tank (TTES)



Pit (PTES)



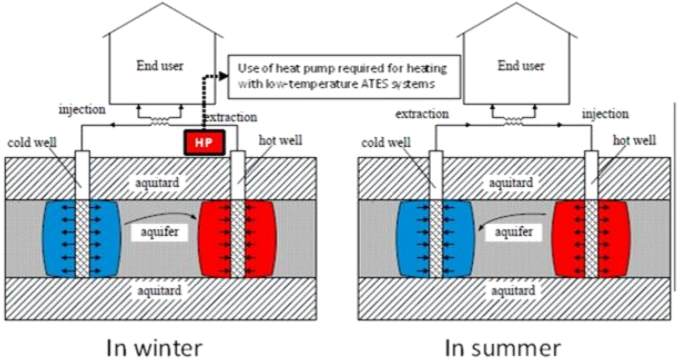
Cavern (CTES)

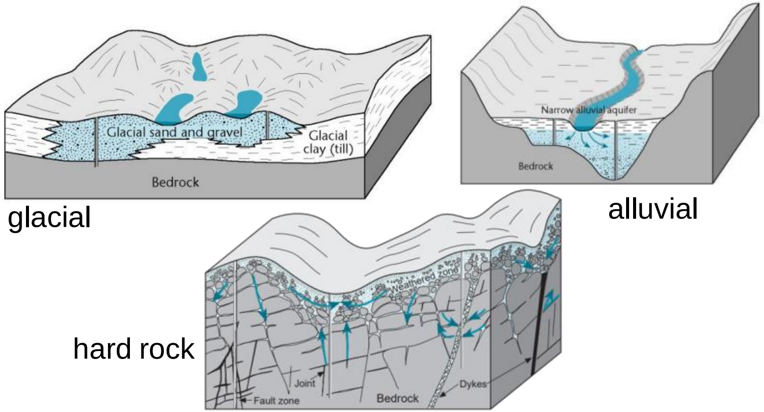


Fractured (FTES)

ATES

- Group of wells in an aquifer
- High hydraulic conductivity required
- Injection/extraction schemes depending on the season
- Ground (matrix) and ground water as storage media
- Heat transfer is both convective and conductive
- glacial vs. alluvial vs. hard rock aquifer





glacial

alluvial

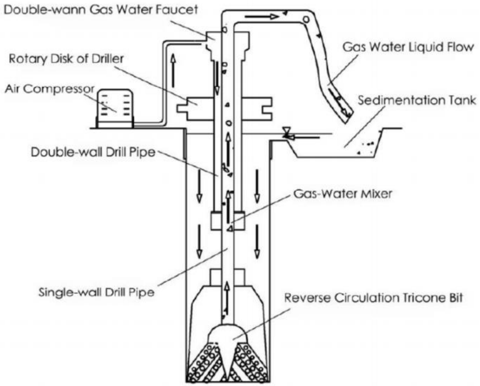
hard rock

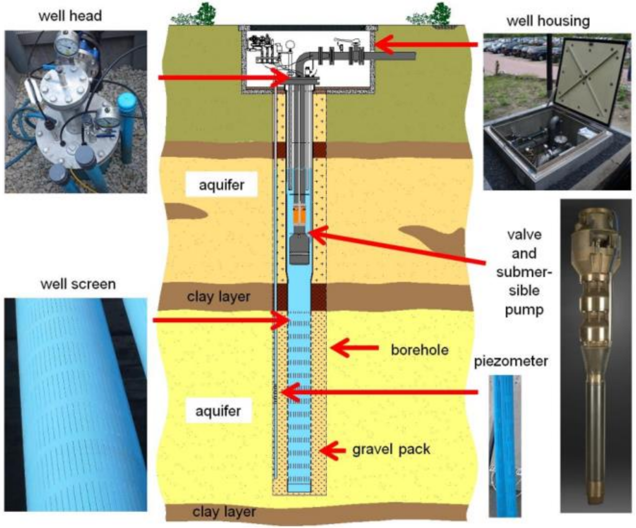
ATES - construction

- Wells drilled into the aquifer
- wells equipped with pumps, production- and injection-pipes
- mineralogy, geochemistry and microbiology

Drilling rig in action

Reverse rotary drilling





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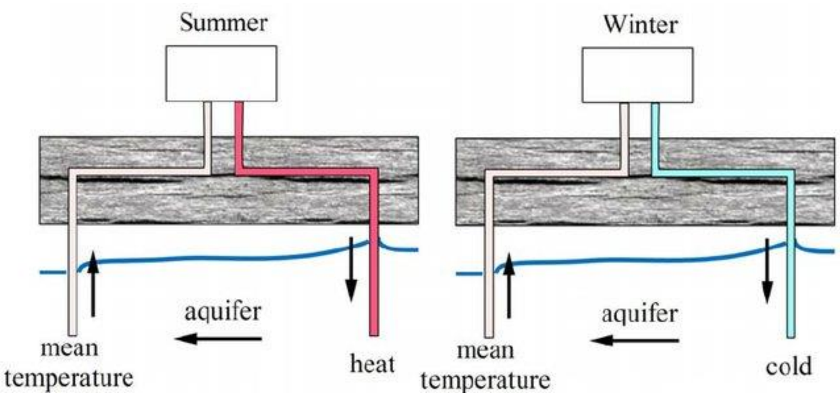
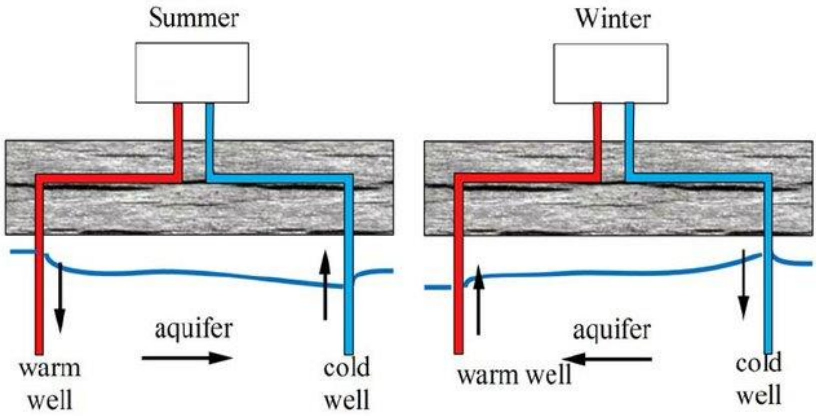
ATES – continuous vs cyclic regime

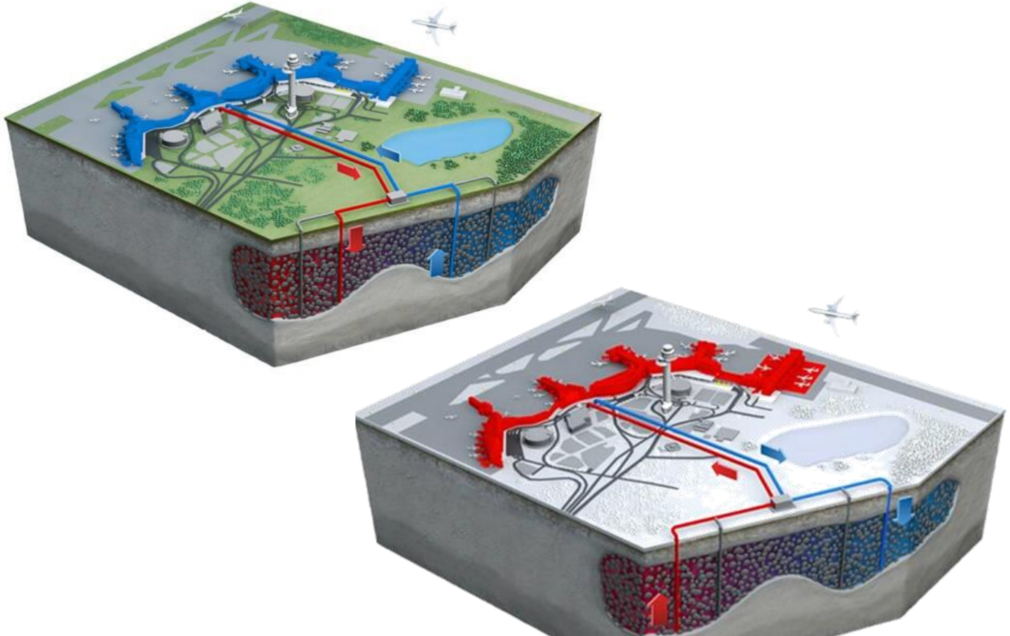
Continuous regime



Cyclic regime

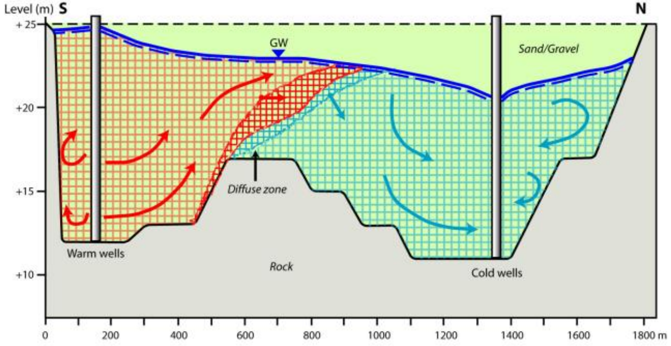


ATES – example 2



Arlanda airport, Sweden

- Heating and cooling
- 11 wells (5 cold and 6 warm)
- Water flow rate 720 m^3/h
- 10-15 GWh
- Payback time 6-7 years



https://underground-energy.com/our-technology/ates/

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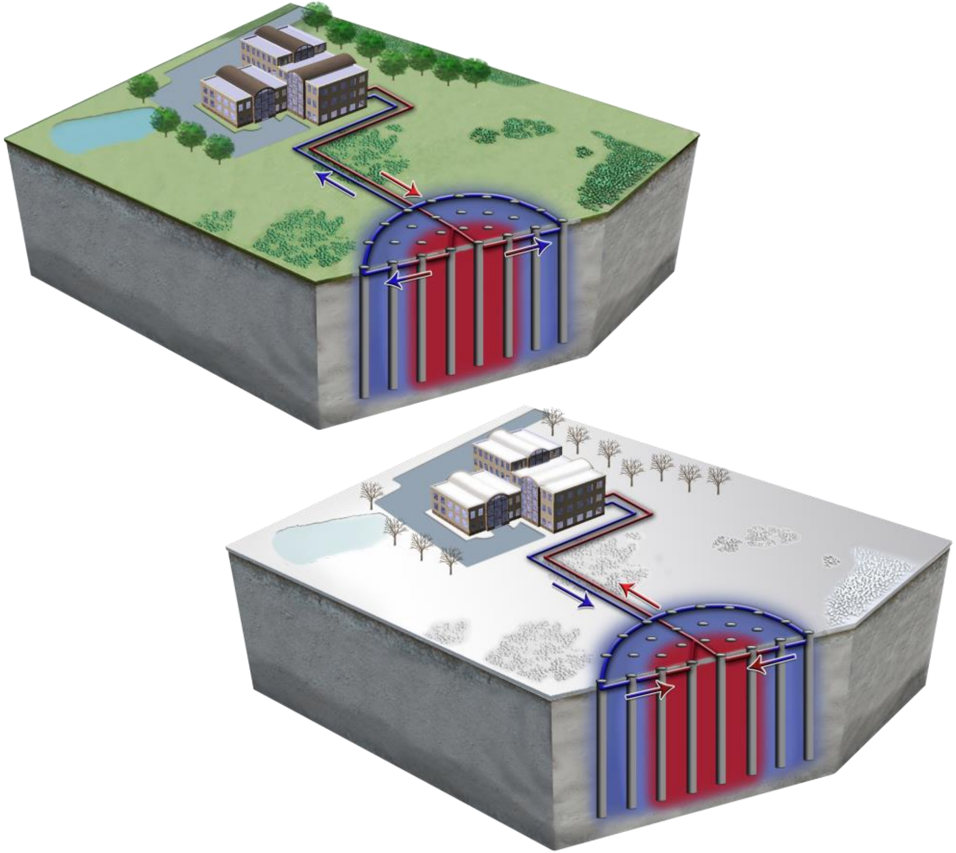
BTES

- Heat is stored directly in the ground via boreholes
- Borehole Heat Exchangers
- No separated storage volume
- Conductive heat transfer
- Rock/soil as the storage medium
- Modular design



https://underground-energy.com/our-technology/btes/

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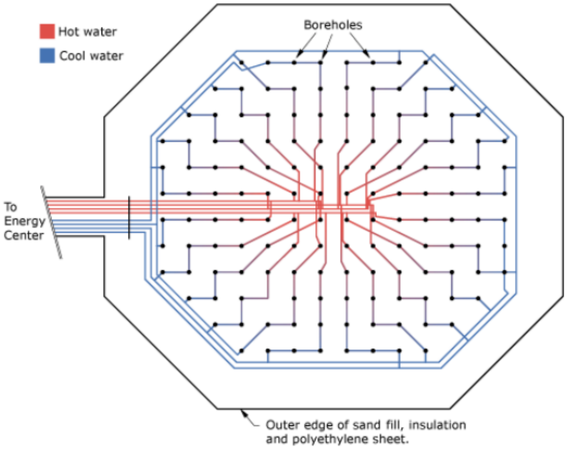
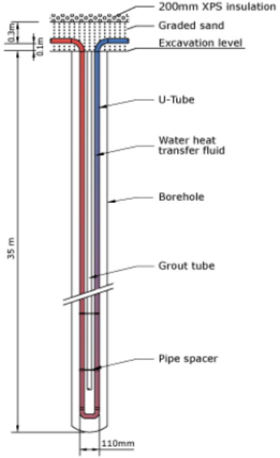
BTES - construction

- shape to maximize the volume to surface area ratio
- heat exchanger u-tubes are connected in series – radial path
- Parallel circuits to distribute the flow
- Charging: flow from center to outer edge; Discharging: vice-versa





http://dlsc.ca/

Nordel et al. 2015

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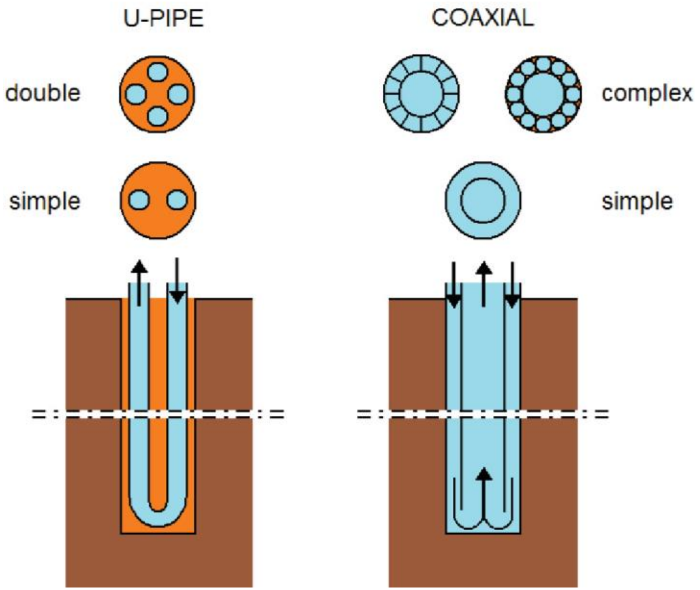
BTES – borehole heat exchanger BHE

- Coaxial
- Single U-tube
- Double U-tube
- Grouted vs. water-filled
- Thermal resistance
- PEX tubes

$$R_b = \frac{T_{f,l} - T_b}{q_b}$$



Scorpo, 2013

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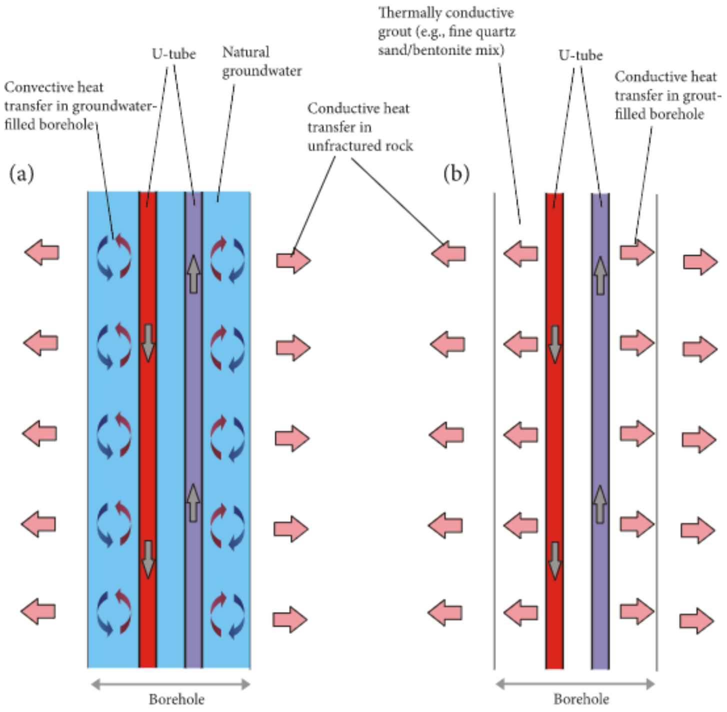
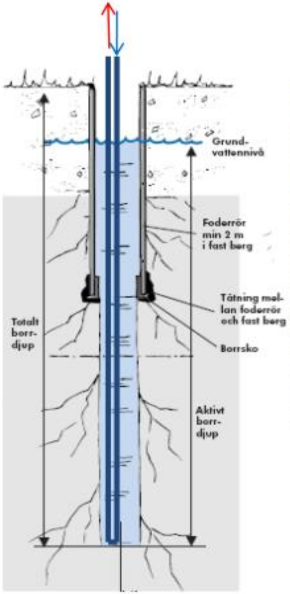
BTES –water-filled vs. grouted boreholes



Skarphagen et al. 2019



http://www.svepinfo.se/

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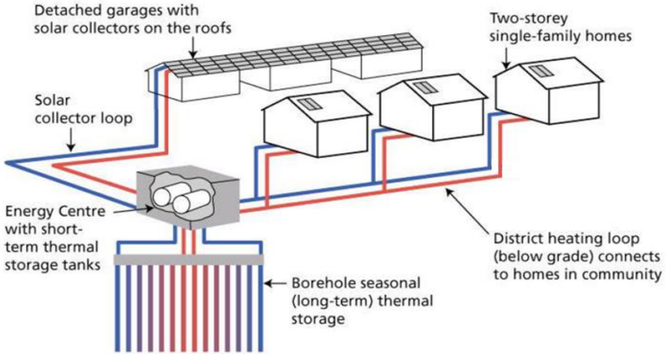
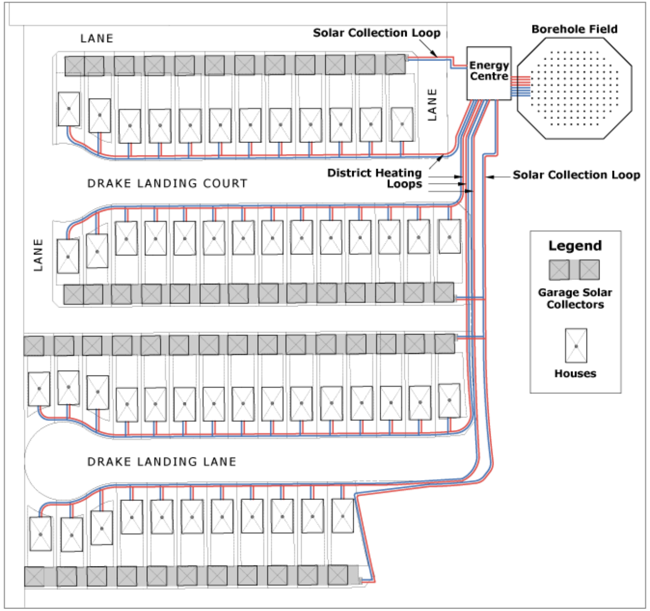
BTES – example

- **DLSC, Canada**
  - Okotoks, Canada
  - 144 boreholes, 35m deep
  - 24 parallel strings with 6 boreholes in series
  - 98% solar fraction, SPH

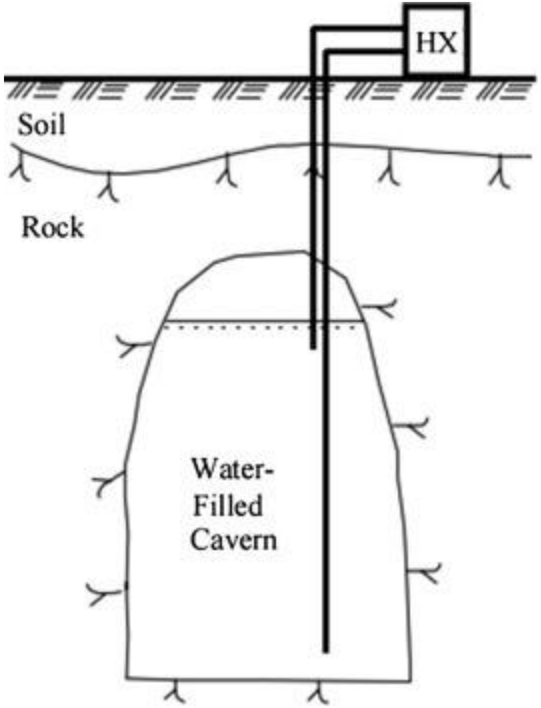




http://dlsc.ca/

CTES

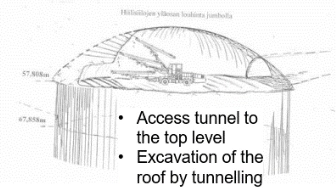
- Large cavern excavated in rock
- High charging/discharging power
- High capital cost
- Good rock conditions required
- reuse of abandoned caverns is possible



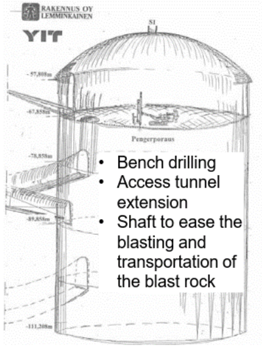
CTES - construction

Excavation of Salmisaari coal storage

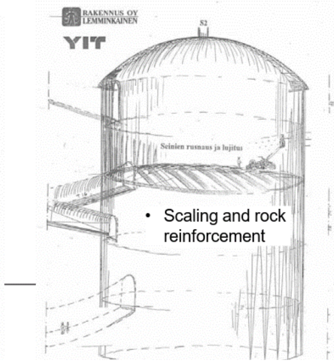
Korhonen, Kari. Salmisaari-case, maanalainen hiilivarasto. Urakoitsijan näkökulma. Kalliolaadun vaikutus louhinnassa ja lujituksessa. Koulutuspäivä 22.5.2002. Suomen kalliomekaniikkatoimikunta.



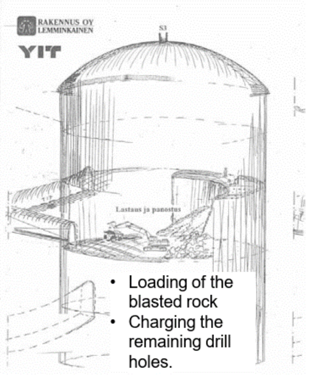
- Access tunnel to the top level
- Excavation of the roof by tunnelling jumbo (D&B)



- Bench drilling
- Access tunnel extension
- Shaft to ease the blasting and transportation of the blast rock



- Scaling and rock reinforcement



- Loading of the blasted rock
- Charging the remaining drill holes.

Surface excavation methods are used also underground

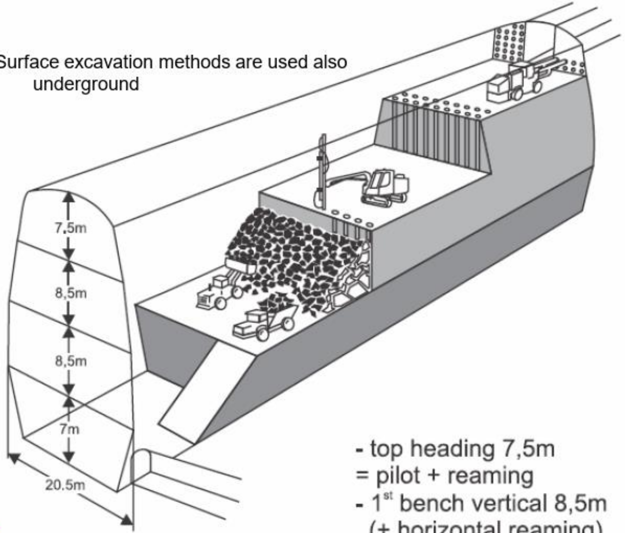


Fig. Rock Excavation Handbook, Sandvik Tamrock 1999.

- top heading 7,5m
= pilot + reaming
- 1st bench vertical 8,5m
(+ horizontal reaming)
- 2nd bench vertical 8,5m
- 3rd bench horizontal/vertical

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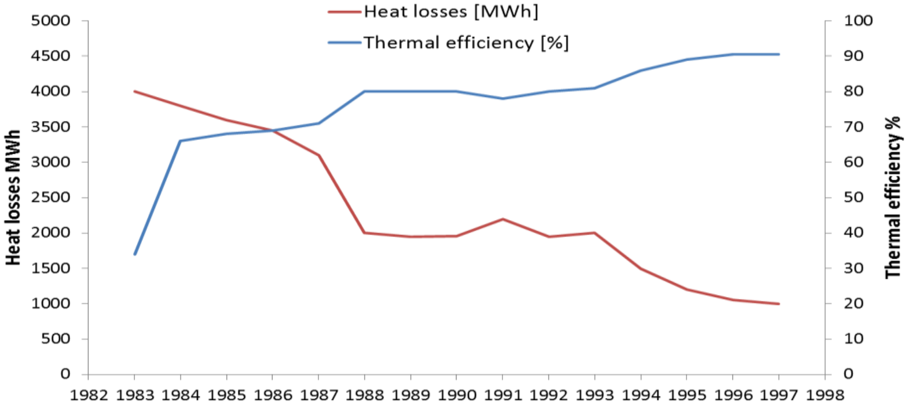
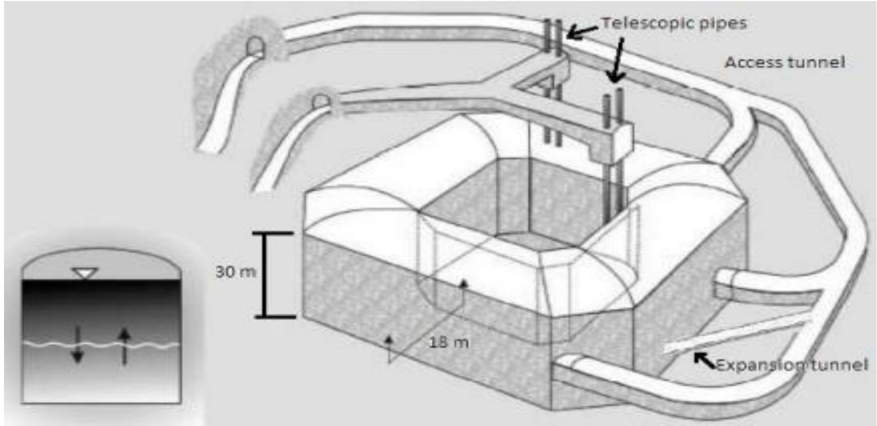
CTES – example 1

Lyckebo, Sweden

- Volume: 104 300 m^3
- Storage capacity: 5.5 GWh
- Temperature: 40-90 °C
- Charge and discharge via telesco pipes
- SPH and DHW
- Cost 4.3 M€





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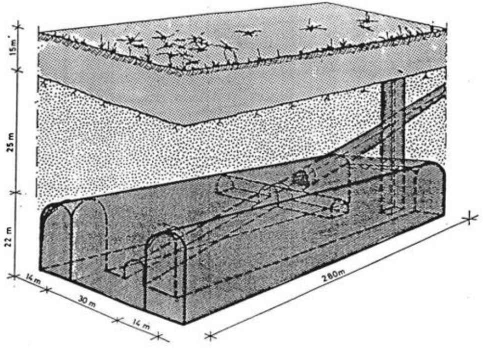
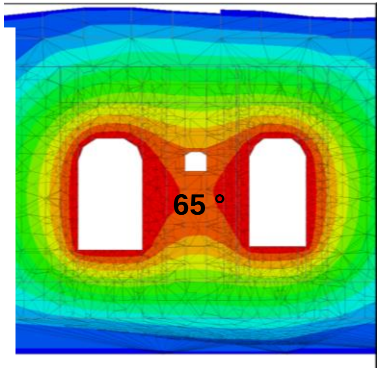
CTES – reuse of abandoned caverns

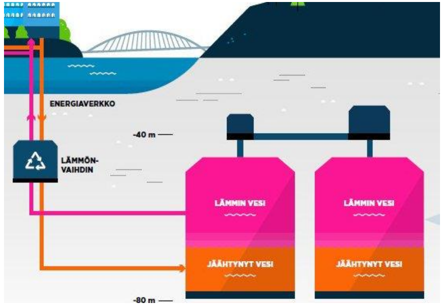


Oulu

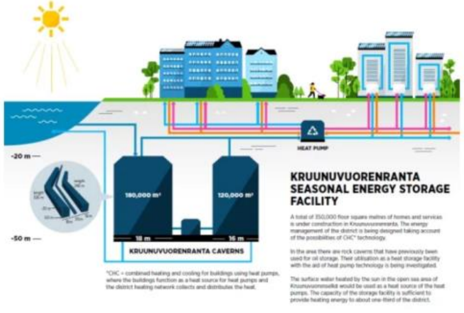


Katariina battery, Kotka

Laukkanen & Lampinen, 2014



Mustikkamaa, Helsinki



KRUUNUVUORENRANTA SEASONAL ENERGY STORAGE FACILITY

A total of 350,000 floor square metres of homes and services is under construction in Kruunuvuorenranta. The energy management of the district is being designed taking account of the possibilities of CHC* technology.

In the area there are rock caverns that have previously been used for oil storage. Their utilisation as a heat storage facility with the aid of heat pump technology is being investigated.

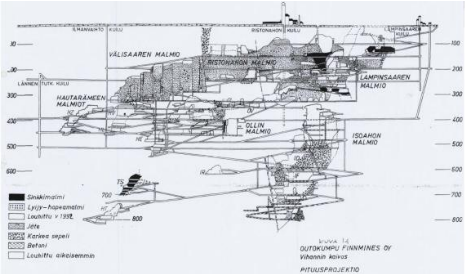
The surface water heated by the sun in the open sea area of Kruunuvuorenselkä would be used as a heat source of the heat pumps. The capacity of the storage facility is sufficient to provide heating energy to about one-third of the district.

*CHC = combined heating and cooling for buildings using heat pumps, where the buildings function as a heat source for heat pumps and the district heating network collects and distributes the heat.

Kruunuvuorentranta, Helsinki

Aspects to consider:

- shape (thermal stratification) vs. mechanical stability
- Interference of multiple caverns



Vihanti mine

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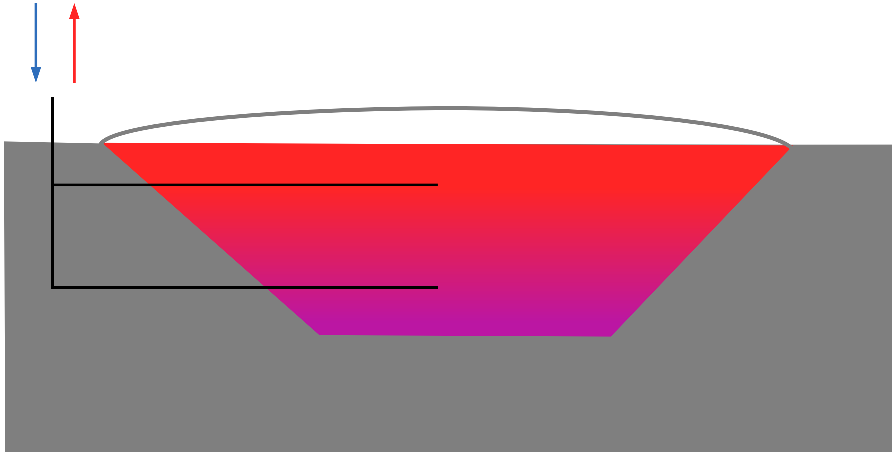
Seppälä, 2016

PTES

- Pit excavated into the ground
- Bottom lined, top covered
- Large storage volumes
- Water as storage medium (sometimes water + gravel)
- Max temperature 90 °C (due to liner)
- Mainly Denmark, Sweden, and Germany



Pit (PTES)

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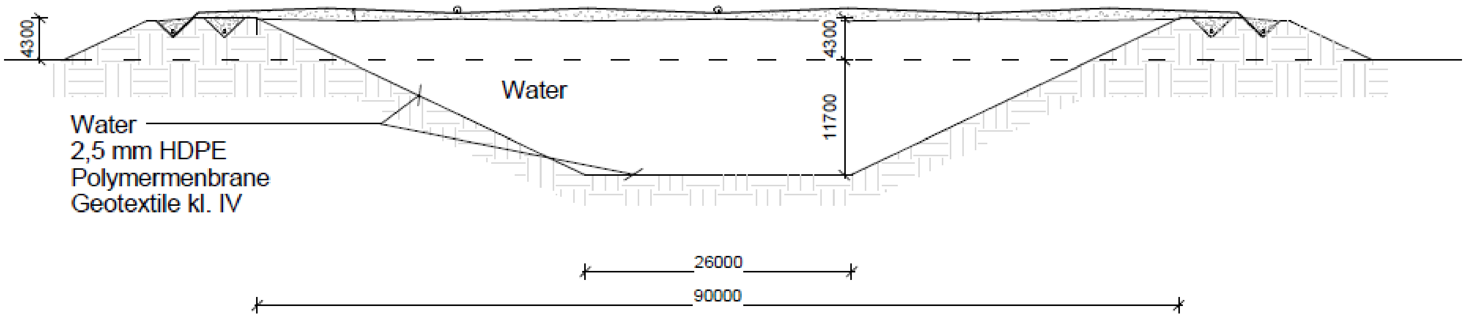
PTES - construction

- Bottom and walls covered with liner
- Floating cover
- Polyethylene lining (Geotextile)

iea-dhc.org



PTES – example

70 000 m^2

Vojens, Denmark

- Seasonal storage
- Solar heating plant SDH
- Old sand pit

200 000 m^3

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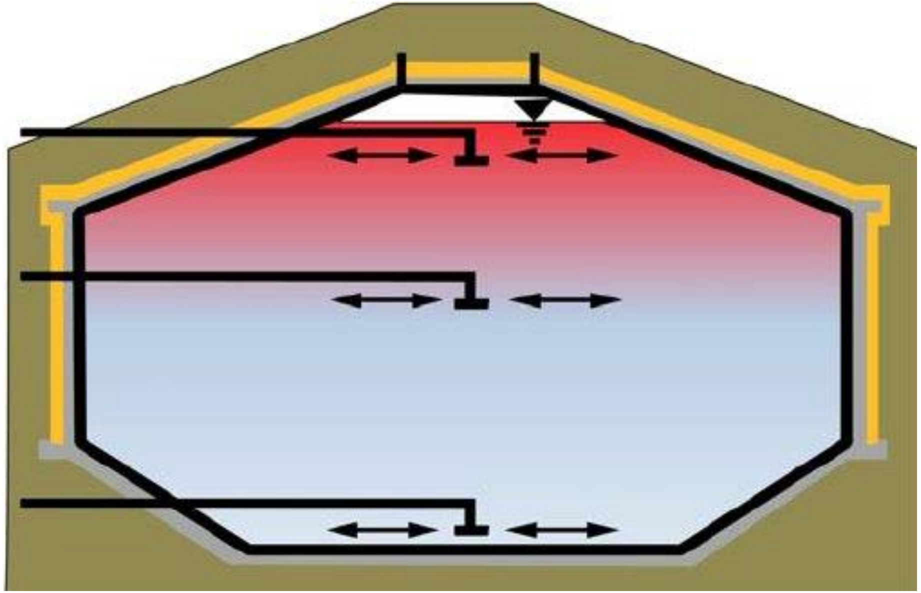
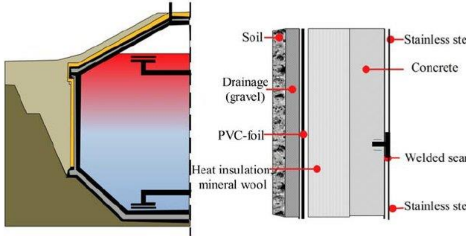
TTES

- Wide range of utilization (independent from geology)
- Water as storage medium
- Three requirements:
  - stratification
  - min. dead water volume
  - min. heat loss/gain

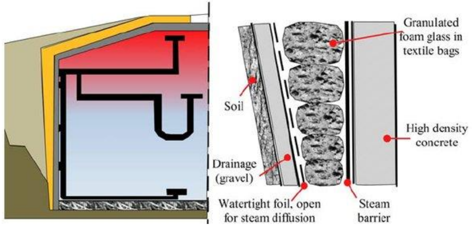


TTES - construction

- Tank built from reinforced concrete or steel
- Fully or partially buried in the ground
- Insulated roof and walls



Construction of the water-tank stores in Friedrichshafen



Construction of the water-tank stores in Hannover

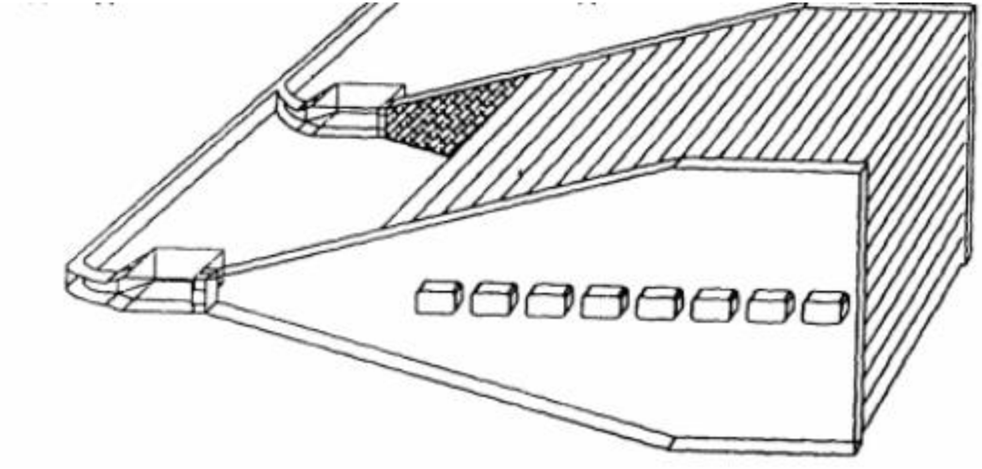
TTES – example

Munich, Germany

- Built in 2007 and ntegrated into district heating system for 300 apartments
- 5700 m^3 volume
- Charged by 3000 m^2 solar collectors
- Prefabricated concrete elements
- Foam glass gravel layer for insulation of the floor, expanded glass insulation in walls
- Stratification device inside the tank

COMBI/HYBRID

- Combine advantages of multiple UTES methods
- Example: CTES + BTES
  - Heat injection/extraction power of CTES
  - Lower cost of BTES



Nordell, 2012

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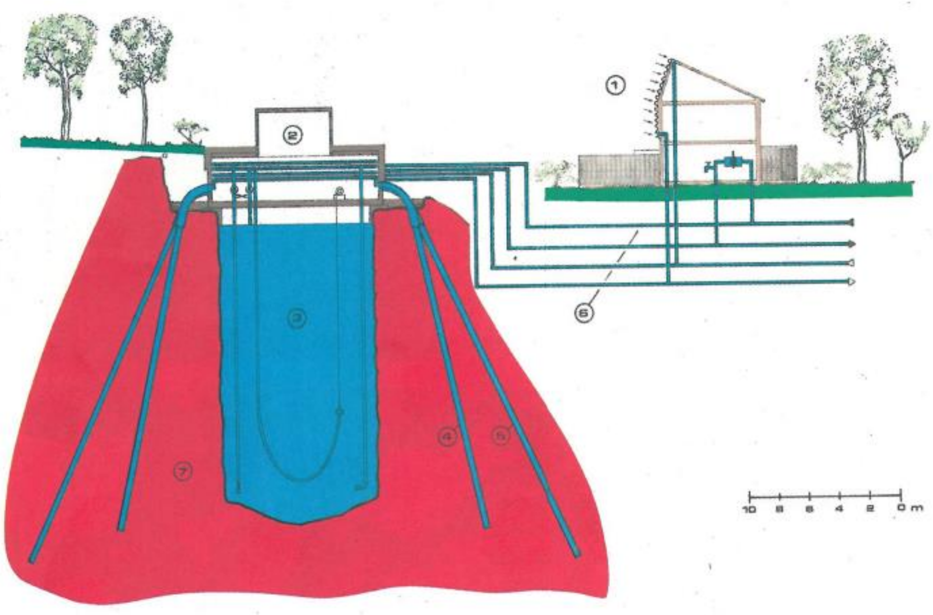
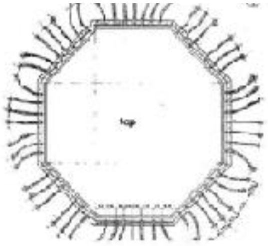
COMBI/HYBRID – example 1

- **Kerava, Finland**
  - Solar village of 44 houses
  - 1500 m^3 Water Storage
  - 11000 m^3 Rock Storage
  - 2 Rings of boreholes (54 in total)
  - Thermally stratified water tank (top 50°C)
  - Energy storage efficiency of 85%
  - Operation from 1983 till 1985

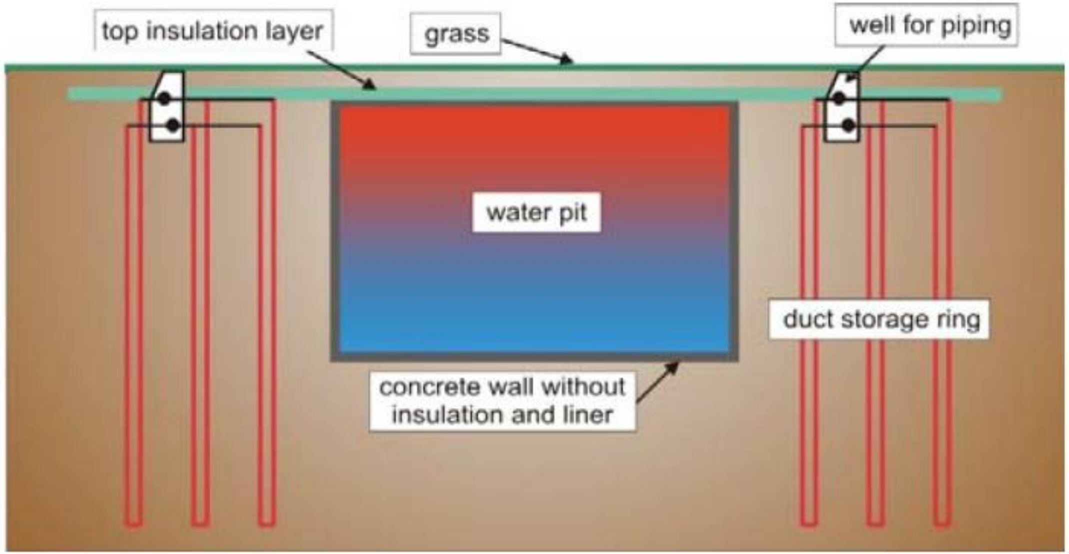




COMBI/HYBRID – example 2

Attenkirchen, Germany

- **Tank**
  - 9 m diameter
  - 8.5 m depth
  - 500 m^3 volume
- **Boreholes**
  - 90 boreholes
  - 30 m deep
  - 3 rings
  - 10 500 m^3 volume
  - double U-tube
- **Cost**
  - 330 k€ storage; 1.2 M€ whole system



Reuss et al. 2006

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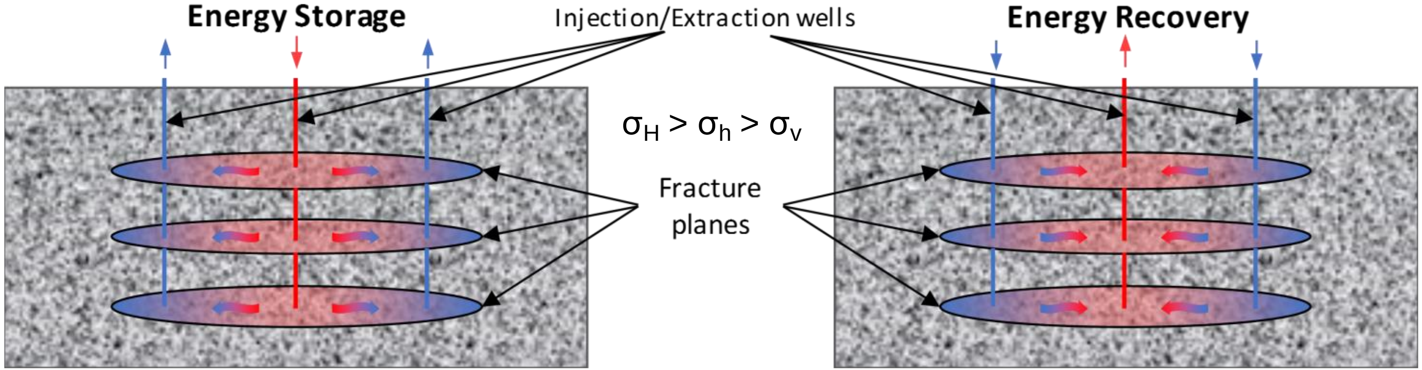
COMBI/HYBRID - concept



Janiszewski et al. 2019

Fractured TES (HYDROCK concept)

- Heat transfer between fluid and rock through parallel sub-horizontal fracture planes
- Hydraulic fracturing in vertical boreholes
- Lower number of borehole required compared to BTES

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Hellström and Larson (2001)

Pros and cons of UTES methods

Method	Pros	Cons
ATES	+ Efficient provision of heating and cooling + Easily integration + Small land footprint	- Hydrogeological restrictions - Limited to places where extraction is possible - Difficult to balance charging and discharging
BTES	+ Seasonal storage + Modular	- Low storage efficiency - Limited charging/discharging power
PTES	+ Potential for very large storage capacity + Seasonal storage	- Low energy density - Large land footprint
CTES	+ High charging/discharging power + Large storage capacity	- Requires hard rock - High capital cost
TTES	+ Scalable + No site restrictions	- Space requirement - High capital cost - Heat loss of small systems

UTES Thermal storage efficiency

Method	Storage efficiency, %
ATES	70 – 90%
BTES	30 – 60%
PTES	up to 80%
TTES	50 – 90%
CTES	40 – 90%

Content

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UTES methods

UTES project

Case study 2:
open stopes

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UTES Project phases

Desktop Feasibility Study	Pre-Design Work	Detailed Design	Construction	Commissioning	Operation, Maintenance & Monitoring
Non-intrusive, look for fatal flaws Preliminary cost estimate	Geologic characterization Thermal modelling of the system	Equipment specification Integration with Mechanical, Electrical & Plumbing systems Detailed cost estimate			

UTES feasibility study

Geological evaluation

Thermophysical and mechanical properties

Hydraulic properties

Engineering evaluation

Cooling/heating configuration

Heating requirements

Size and capacity

Conceptual design

Efficiency

Energy and emissions reductions

Construction and installations

Safety

Financial evaluation

Construction cost

Resources use

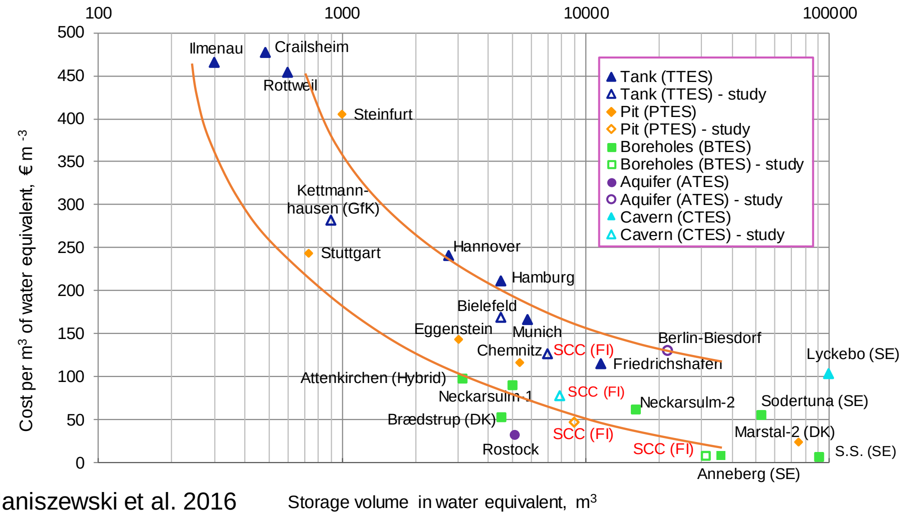
Financial benefit (Net Present Value)

Regulatory evaluation

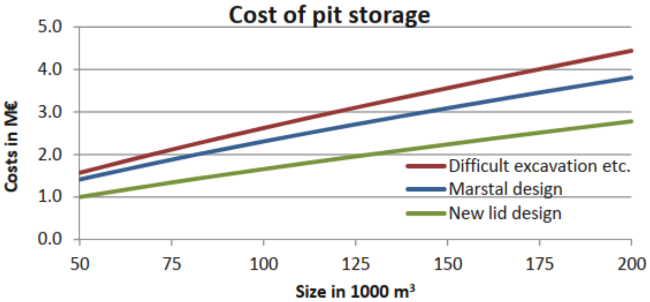
Environmental standards

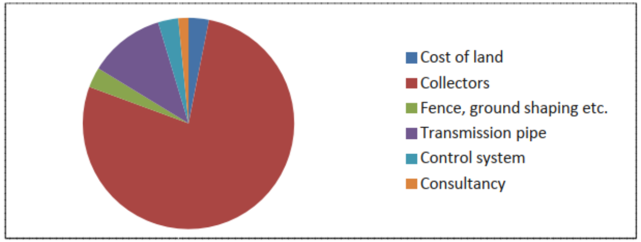
Identification of required permits

UTES Costs

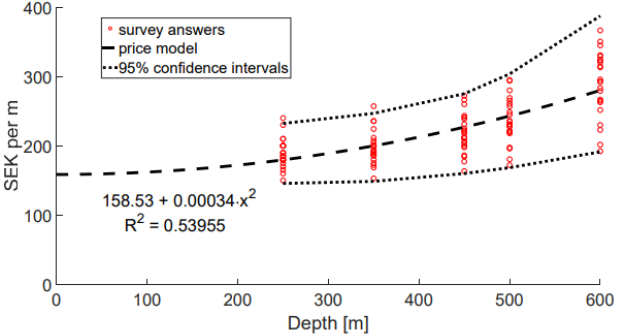


Janiszewski et al. 2016





Example of cost distribution (Tørring, DK). Note that storage is not included. (Source: PlanEnergi)

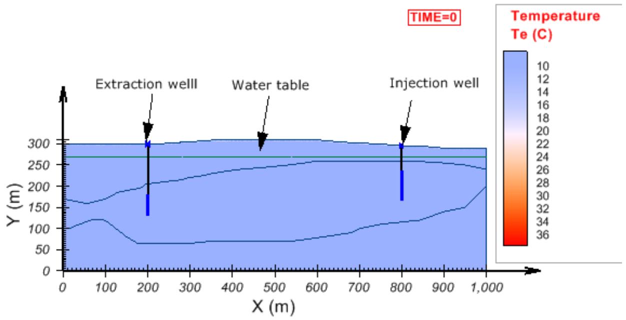


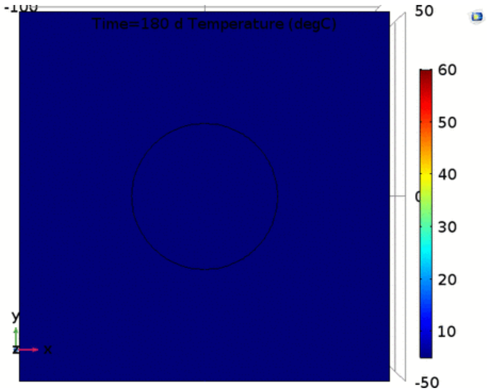
Mazotti et al. 2018

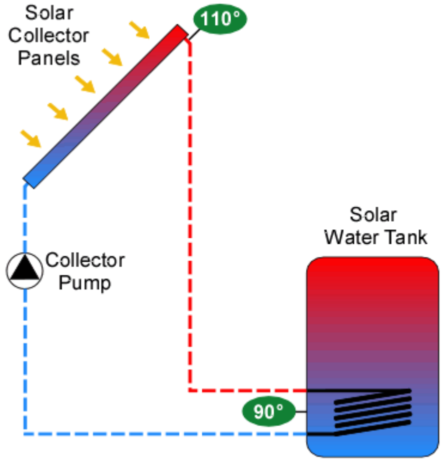
The cost of the planning, designing & optimization is approximately 2-5 % of the total investments

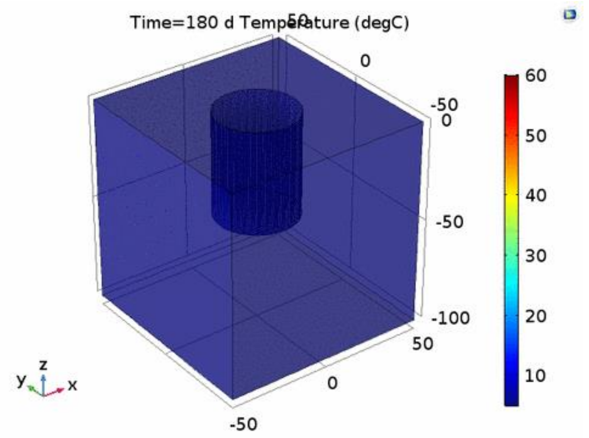
The investment, maintenance and operational cost have to be related to its thermal performance in the overall system!

Numerical simulation as a design tool









Evaluation of different storage methods

Evaluation criteria	ATES	BTES	CTES	PTES	TTES
Simplicity of obtaining sufficient storage volume	+++	+++	++	++	++
Economics	+++	++	+	+	+
Storage efficiency	++	+	+++	++	++
Site requirements	+	++	++	++	+++
Adaptability	++	+++	+	+	+
Small scale feasibility	+++	+++	+	+	+++
Simplicity of the storage system	+++	+++	++	+	+

Honkonen, M. 2015. Thermal energy storage concepts and their feasibility. Master’s thesis. Aalto University.

Group Exercise 1

Task: Suggest appropriate UTES method for case A and B. Justify your selection.

Case A

- Solar thermal energy
- Seasonal storage
- 100 houses
- Rock + unknown soil depth

Case B

- District heating network
- Short term storage (to balance variable heat) consumption
- City with 500k inhabitants

Content

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Learning goals

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Case study 1: tunnels

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Thermal properties of rocks

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Why do we need to know what is in the ground?

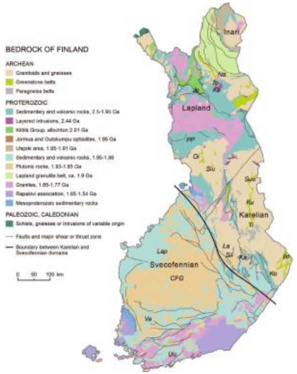
- What is the lithology? – soil, rock?
- Thermal properties of ground
- Groundwater flow
- Soil depth fluctuation
- Method selection depends on site specific conditions

The higher the heat capacity, the more heat can be stored in the ground

⬇

Site investigations are crucial in UTES projects!

Site investigations - examples

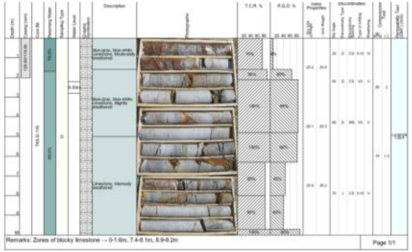


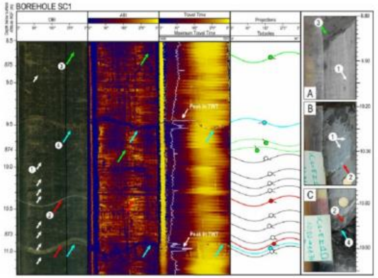
EXISTING DATA

TEST HOLES (WELLS)

ROCK/SOIL SAMPLING

BEDROCK DEPTH





BOREHOLE IMAGING

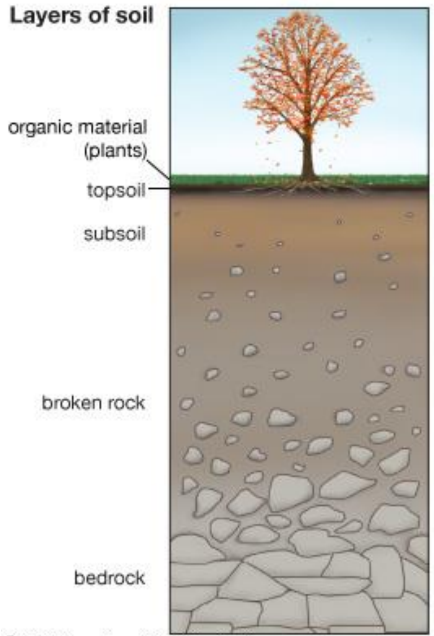
THERMAL CONDUCTIVITY AND HEAT CAPACITY

THERMAL RESPONSE TEST (TRT)

GROUNDWATER

Soil depth

- soil depth can fluctuate by few meters in a small area
- especially important in BTES!
  - **Drilling cost with casing costs 3-4 times as much as drilling in hard rock**
- determine the soil depth, for example using a geo-radar or seismic profiling



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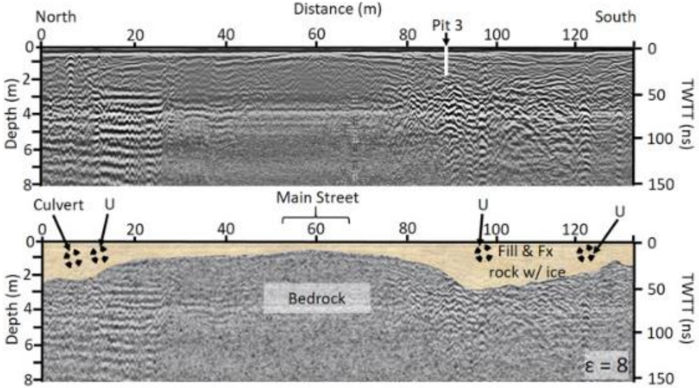
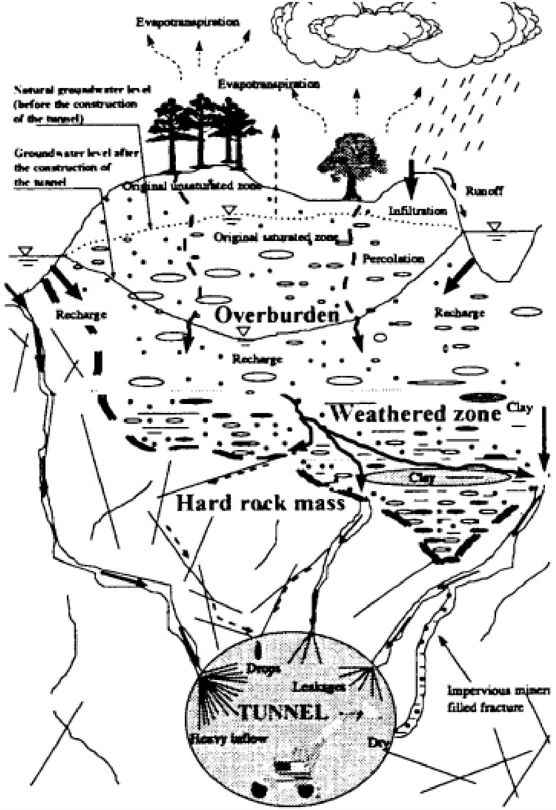


Campbell et al. 2018

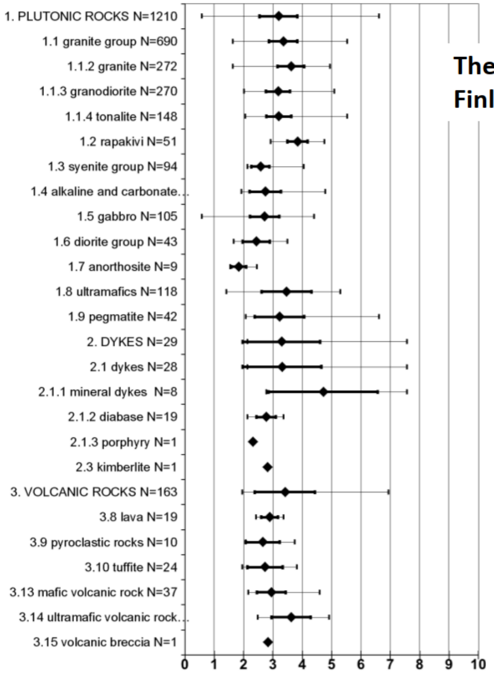
Fractures and ground water flow

- High groundwater flow may lead to high heat losses
- GW in bedrock takes place in fractures
- Grouting in boreholes may be required if fractures with groundwater flow are present
- Maps, outcrops, test boreholes, permeability tests



Cesano, 1999

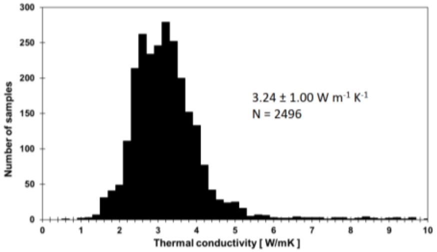
Thermal properties of rocks in Finland



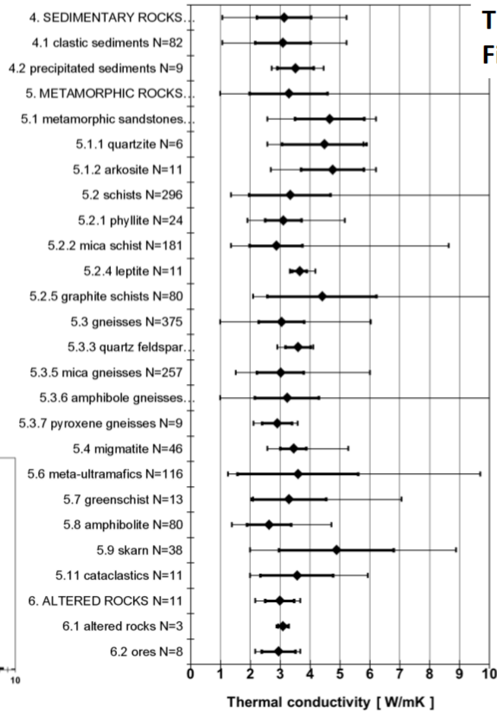
Thermal conductivity of rock types in Finland: Mean, std and range

Plutonic rocks
Dykes
Volcanic rocks

- Wide ranges within single rock types



Thermal conductivity of rock types in Finland: Mean, std and range



Sedimentary rocks
Metamorphic rocks
Altered rocks

- Wide ranges within single rock types
- Std is typically 0.5 – 1 $Wm^{-1}K^{-1}$
- Message to take home: Rock type is not a short-cut to thermal conductivity!
- Measurements are necessary

S. Peltoniemi, 1996;
Kukkonen and Peltoniemi, 1998

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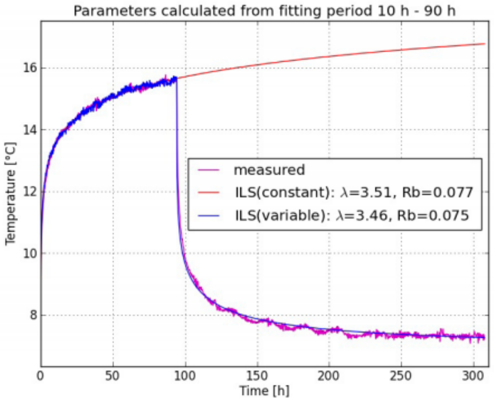
Thermal response testing (TRT, DTRT)

TRT provides an average (effective) **thermal conductivity** of the storage volume as well as the **thermal resistance of the borehole**

DTRT (Disturbed TRT) for more detailed analysis of anisotropic and heterogenous environments – provides layered thermal conductivity and borehole thermal resistance

- borehole
- circulation pump + pipe system
- heater with constant power rate
- continuous logging of the inlet and outlet temperatures of the flow

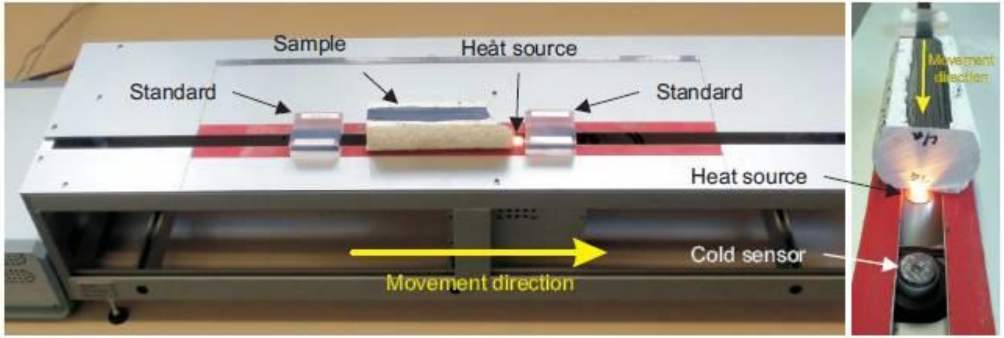


gtk.fi

Measurements of thermal properties

$$s = \frac{\lambda}{\rho c}$$

where
s is thermal diffusivity ($m^2\ s^{-1}$)
λ is thermal conductivity ($W\ m^{-1}\ K^{-1}$)
c is specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
ρ is density ($kg\ m^{-3}$)

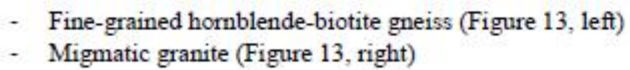


Typically two of the three thermal properties are measured and the third one is calculated (density must be known or measured)

Example test: Thermal (optical) scanning

- thermal conductivity and thermal diffusivity

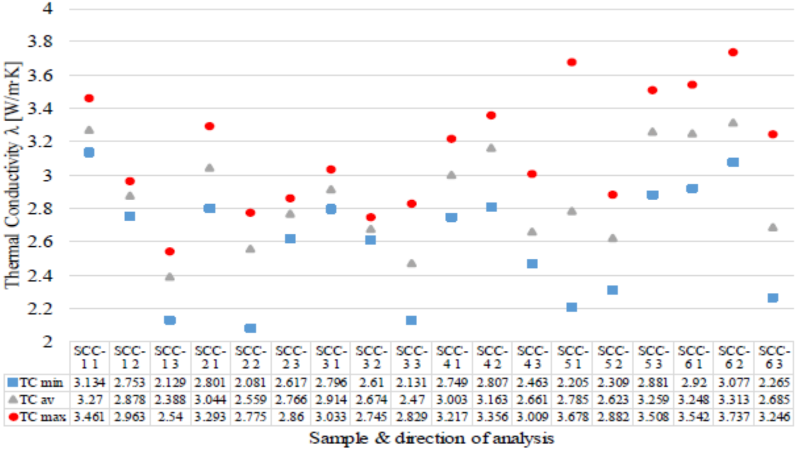
Thermal conductivity lab test



- Fine-grained hornblende-biotite gneiss (Figure 13, left)
- Migmatic granite (Figure 13, right)

λave = **2.87 W/m·K**

Cp = **723.5 J/kg·K**



	SCC-1 1	SCC-1 2	SCC-1 3	SCC-2 1	SCC-2 2	SCC-2 3	SCC-3 1	SCC-3 2	SCC-3 3	SCC-4 1	SCC-4 2	SCC-4 3	SCC-5 1	SCC-5 2	SCC-5 3	SCC-6 1	SCC-6 2	SCC-6 3
■ TC min	3.134	2.753	2.129	2.801	2.081	2.617	2.796	2.61	2.131	2.749	2.807	2.463	2.205	2.309	2.881	2.92	3.077	2.265
▲ TC av	3.27	2.878	2.388	3.044	2.559	2.766	2.914	2.674	2.47	3.003	3.163	2.661	2.785	2.623	3.259	3.248	3.313	2.685
● TC max	3.461	2.963	2.54	3.293	2.775	2.86	3.033	2.745	2.829	3.217	3.356	3.009	3.678	2.882	3.508	3.542	3.737	3.246

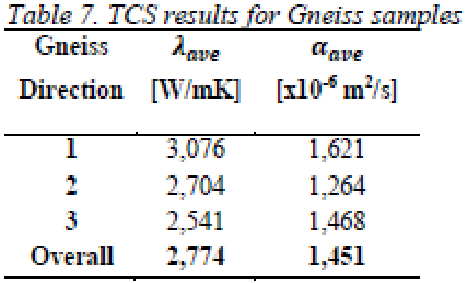


Table 7. TCS results for Gneiss samples

Gneiss Direction	λ_{ave} [W/mK]	α_{ave} [x10^{-6} m^2/s]
1	3,076	1,621
2	2,704	1,264
3	2,541	1,468
Overall	2,774	1,451

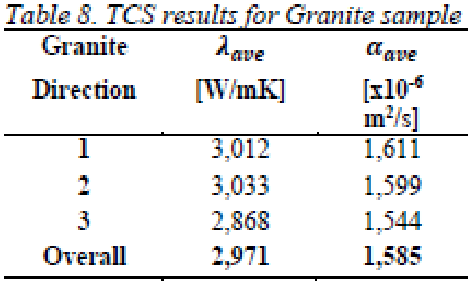


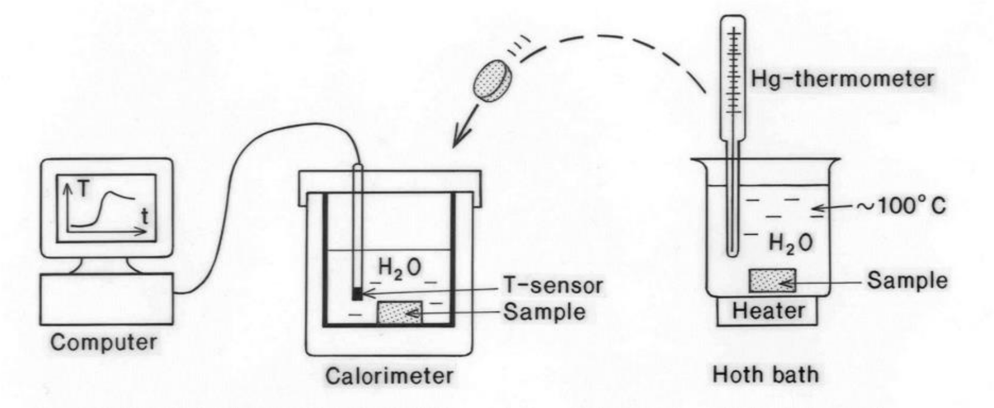
Table 8. TCS results for Granite sample

Granite Direction	λ_{ave} [W/mK]	α_{ave} [x10^{-6} m^2/s]
1	3,012	1,611
2	3,033	1,599
3	2,868	1,544
Overall	2,971	1,585

Caballero Hernandez (2017) In situ experimentation and numerical model validation of thermal flow in shallow crystalline rock, Otaniemi case, Master's thesis

Heat capacity lab test

- In the simplest application specific heat capacity is determined with a calorimeter
- The application used at Geological Survey of Finland:
- Heating of the sample (about 25-30 g piece of rock, i.e. thermal conductivity sample) in boiling water
- Calorimeter contains 100 g of water at room temperature
- Final temperature of the calorimeter after adding the sample is determined



Kukkonen, 2016

Group Exercise 2

Task: Suggest a preliminary site investigation plan for BTES project in Southern Finland

- **What should be measured and why?**

Group Exercise 2

Thermophysical and mechanical properties of the ground and aquifer

- Soil/rock types
- Bedrock depth (drilling cost)
- Thermal conductivity (TRT)
- Discontinuities (is grouting needed?)

Hydraulic properties

- Groundwater elevation
- Groundwater flow
- (Geochemistry)???

Summary

- UTES can help to correct the mismatch between supply and demand of energy
- Various methods: BTES, ATES, CTES, PTES, TTES, Hybrid/Combi
- Selection of the method depends on the site-specific conditions
- Site investigations plan is crucial
- Coordinated set of actions is needed to realize the maximum benefits of UTES

Relevant additional reading

Lee (2013) Underground thermal energy storage. Springer

Cabeza (2014) Advances in thermal energy storage systems: methods and applications. Elsevier – ch.1, 2, 5, 6, 7

Dincer & Rosen (2010) Thermal energy storage: systems and applications. Wiley. – ch.3, 4, 5, 7.4, 7.5

Banks, (2012) An Introduction to Thermogeology: Ground Source Heating and Cooling

Kallesøe, A.J. & Vangkilde-Pedersen, T. (eds). 2019: Underground Thermal Energy Storage (UTES) – state-of-the-art, example cases and lessons learned. HEATSTORE project report