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D2.2 Report on construction techniques

1. Introduction

Sensible Heat Storage is the most common method of thermal energy storage, particularly in the form of hot water tanks. Essentially, sensible heat storage systems work by charging them with heat from a higher temperature source to raise the temperature of the thermal store, and by extracting heat to discharge them.

On a larger scale, these sensible heat stores should be designed to store heat long term over seasons, which allow the thermal storage systems to be charged using solar thermal systems to then supply heat over colder periods and can be applied in an array of buildings, including individual dwellings and larger buildings. These seasonal storage systems consist of: Tank Thermal Energy Storage (TTES), Pit Thermal Energy Storage (PTES), Borehole Thermal Energy Storage (BTES) and Aquifer Thermal Energy Storage (ATES).

The aim of this report is to provide useful information about the different construction techniques for the mentioned systems in addition to FP7 Einstein Project, where a big information research has already been done, analysing the main characteristics that interfere in the various proceedings.

For TTES and PTES, information of the characteristics and properties of insulation materials and layers are studied, as well as building integration of the tanks in new or existing construction whose accessibility could limit the storage volume. At this point, a compilation of the variety of tanks that the market offers is made.

Concerning BTES and ATES soil parameters play an essential role in the efficiency of the system, those are analysed and then different system's configuration are described.

Regarding the internal structure of the tanks, stratification and heat exchangers devices and designs are analysed as well as the PCM implementation, gathering different options and recommendations.

In addition, a general study for the three different CHESS-SETUP pilots is done regarding the availability and constraints of every case to introduce the different technologies.

Finally, in order to ensure the correct operation of the installations, some guidance of the different types of maintenance is done as well as maintenance plans for the different elements of the system.

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2. TTES and PTES construction

2.1. Storage Systems

Making a quick review of D2.1 for these two storage systems, the Tank Thermal Energy Storage (TTES) is the one with the widest range of utilization possibilities and that can be built almost independently from geological conditions, but it must as much as possible avoid groundwater as it will encourage heat transfer and degrade the structure over time. Typical depths are from 5 to 15m and the heat storage capacity is between 60 and 80kWh/m3.

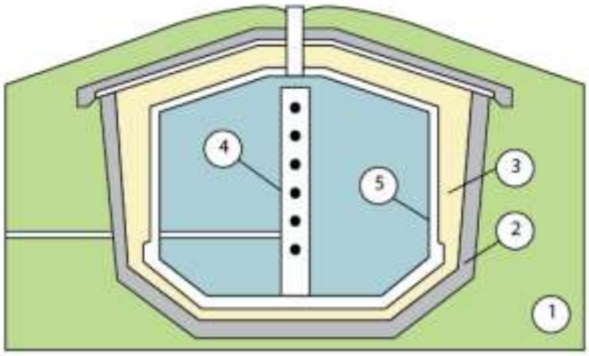

Figure: Tank thermal energy storage system.
[1]soil; [2] reinforced concrete; [3] insulated layer; [4] stratification pipe; [5] steel layer (Source: D2.1)

Seasonal TTES usually have a tank construction built of reinforced concrete, heat insulated at least in the roof area and on the vertical walls. It is usually built as steel or reinforced pre-stressed concrete tank, fully or partially buried in the ground.

Figures: Seasonal thermal storages of the Einstein Project

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Figure: Construction of a TTES in Germany and integration of a TTES into the landscape (Source D2.1)

On the other hand, Pit Thermal Energy Storage (PTES) consists in a large and enclosed artificial pond where the sides are covered with thermal insulation material. PTES are dug into the ground, but close to the surface in order to reduce excavation costs. The slope angle of the side walls depend on the nature and density of the supporting soil.

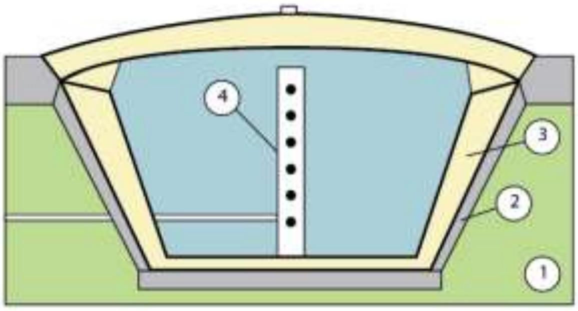

Figure: Pit thermal energy storage (PETS) system.
[1]soil; [2] reinforced concrete; [3] insulated layer; [4] stratification pipe (Source: D2.1)

These systems are also almost independent from geological conditions, with once again avoiding ground water as much as possible. Depths are from 5 to 15 m and the pit thermal energy storage is filled with water or gravel-water mixture (gravel fraction 60-70%). The heat storage capacity with gravel-water mixture is between 30 and 50 kWh/m3 (equivalent to 0.5-0.77 m3 of water).

Figure: Pit storage construction in Eggenstein, 2008 (4,500 m3)(Source: D2.1).

The shape and dimensions of these storage tanks are very varied and depend on each project requirement, space availability and construction technique.

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2.2. Insulation layers

Thermal insulation materials can take a substantial part within the costs investments (material) and costs savings (energy) balance in case of a relatively high temperature difference between the inside and outside of the construction, which especially applies in case of seasonal heat storage systems.

Thermal insulation materials in building constructions, applied in an environmental temperature area and relatively small temperature difference such as the indoor and outdoor temperature, can also be applied for seasonal storage systems in case that the insulation material has a relatively high thermal conductivity and temperature resistance.

There are some thermal insulation materials, by origin and applied in the construction sector:

Mineral Substances	Plastic Substances	Vegetal Substances
Calcium carbonate	Aerogel	Cellulose fibre
Cellular concrete	Expanded polystyrene (EPS)	Clay (expanded)
Cellular glass (CG)	Extruded polystyrene (XPS)	Cork
Glass fibre	Phenolic foam (PF)	Cotton
Mineral wool (glass)	Polycarbonate (PC)	Flax
Mineral wool (stone)	Polyester (PES) fibre	Hemp fibre
Perlite	Polyethylene (PE)	Sheep's wool
Vermiculite	Polyisocyanurate (PIR)	Straw
	Polymethyl metacrylate (PMMA)	
	Polypropylene (PP)	
	Polyurethane (PU)	
	Polyvinyl chloride (PVC)	
	Urea formaldehyde (UF)	

2.2.1. Thermal insulation performance

The coefficient of heat conduction or lambda value λ (W/mK) is a physic propriety of the materials that measures the thermal conduction. The higher the coefficient of heat conduction is, the material offers a higher thermal conductivity.

With this λ value and the insulation material thickness d (m), the thermal resistance is determined:

$$R = \lambda/_{d} \ (m^2K/W)$$

In the construction sector the following insulation materials are used or developed:

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Material	λ(W/mK)
Aerogel	0.013-0.014
Calcium carbonate	0.076
Cellular concrete	0.076-0.112
Cellular concrete in-situ sprayed (600-1200 kg/m3)	0.122-0.547
Cellular glass (CG)	0.038-0.050
Cellulose fibre (dry blown 24kg/m3)	0.035-0.046
Cellulose fibre (recycled)	0.035-0.047
Cellulose wood fibre (WF)	0.039-0.061
Clay (expanded) (340-750 kg/m3)	0.100-0.150
Cork	0.037-0.040
Cork (120kg/m3)	0.041-0.055
Cork (expanded) (100-200 kg/m3)	0.034-0.040
Cotton	0.039-0.040
Cotton (recycled) Metisse	0.038
Expanded Polystyrene (EPS) (<30kg/m3)	0.030-0.045
Expanded Polystyrene (EPS) BioFoam	0.034
Expanded Polystyrene (EPS) with graphite (grey)	0.030-0.032
Extruded Polystyrene (XPS) with CO2	0.025-0.037
Extruded Polystyrene (XPS) with HFC (35kg/m3)	0.029-0.031
Flax	0.035-0.040
Flexible thermal linings	0.040-0.063
Foils	*
Glass fibre in-situ sprayed	0.035
Hemp fibre	0.038-0.042
Hemp lime (monolithic)	0.067
Mineral wool (glass) (<48kg/m3)	0.030-0.044
Mineral wool (glass) (>48kg/m3)	0.036
Mineral wool (stone) (<160kg/m3)	0.034-0.038
Mineral wool (stone) (>160kg/m3)	0.037-0.040
Perlite	0.040-0.051
Perlite (expanded) board	0.050-0.052
Phenolic foam (PF)	0.020-0.025
Phenolic foam (PF) foil-faced	0.020-0.023
Polycarbonate (PC) TIM	-
Polyester (PES) fibre	0.035-0.044
Polyethylene (PE)	0.035-0.036
Polyisocyanurate (PIR) (<32kg/m3)	0.025-0.028
Polyisocyanurate (PIR) foil-faced (<32kg/m3)	0.022-0.023
Polyisocyanurate (PIR) in-situ sprayed	0.023-0.028
Polymethyl metacrylate (PMMA) TIM	0.074-0.082
Polypropylene (PP)	0.036

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Polyurethane (PU) with pentane (<32kg/m3)	0.027-0.030
Polyurethane (PU) with pentane foil-faced (<32kg/m3)	0.020
Polyurethane (PU) soy-based	0.026-0.038
Polyurethane (PU) with CO2	0.035
Polyurethane (PU) in-situ sprayed/injected	0.023-0.028
Polyvinyl chloride (PVC)	-
Sheep's wool (25kg/m3)	0.034-0.054
Straw bale (monolithic)	0.047-0.063
Strawboard (420kg/m3)	0.081
Urea formaldehyde (UF) (8-20 kg/m3)	0.026-0.054
Vacuum cavity	0.001-0.054
Vacuum insulated panel (VIP)	0.004-0.008
Vacuum super insulation (VSI)	0.004-0.008
Variable conductance insulation (VCI)	0.002-0.007
Vermiculite	0.039-0.060

*no official insulation value available

2.2.2. Temperature and aging impact

The temperature within the insulation material layer will vary with the internal temperature difference between the inside and outside of the layer, and with the external temperature variation at the inside and outside of the layer. The thermal conductivity and lambda value (W/mK) within the insulation material layer will increase by its higher temperature, and by its increasing aging. The lambda value (W/mK) for insulation material used in the construction sector is normally set on a 10˚C temperature and a 30 year age.

2.2.3. System environmental impact

In order to determine the environmental impact of a single material, a Life Cycle Analysis (LCA) should be carried out by a qualified expert. The LCA results in indicators for the environmental impact of a product that are combined into a single value: the shadow costs per unit of product (kg, m3, m2 or the like).

The environmental impact of the energy system can be also analysed by settling the heat demand and the solar collector surface, and in this setting calculating the external energy input into the energy system for different insulation materials. In this way the different environmental impacts of the insulation materials, and its required external (gas or electric) energy inputs, can be compared.

2.2.4. Storage Heat Losses

Especially for a seasonal storage system, with its characteristic upload and unload only once per year, the heat losses by the storage system surface, compared to the heat load within the storage system volume, can be significant.

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A 50m3 storage tank (9.00 m height, 2.65 m diameter, 86 m2 wall surface) with an annual 50 to 90 ˚C temperature curve and 8.4 GJ heat load for example gives, at an annual average storage temperature of 70 ˚C with a temperature difference of 50 ˚C with the 20 ˚C indoor space, and a U-value of 0.080 W/m2K, an average heat loss of 4.00 W/m2, that gives an annual heat loss of 3,013 kWh or 10.8 GJ for 86 m2 wall surface during 8760 hours. In an optimal embodiment, this heat loss benefits to the building.

In case that the storage heat losses are compared with the heat load of a monthly, weekly or daily storage the impact will be less significant, and gradually be 12, 52, and 365 times less significant compared to an annual (seasonal) storage.

The storage heat losses can be calculated with the following dimensions and values:

- Storage dimensions

Height	H	-	m
Width	W	-	m
Length	L	-	m
Surface	A	-	m2

- Thermal resistance

Insulation thickness	t=0.5 m
Thermal conductivity	λ=0.040 W/mK
Thermal resistance (t/λ)	R=12.50 m2K/W
U-value, k-value (1/R)	U=0.080 W/m2K

- Heat losses

Average temperature storage	Ts=70˚C
Average temperature environment	Te=20˚C
Temperature difference (Ts-Te)	Td=50˚C
Heat losses (UxTd)	P=4.00 W/m2

Heat losses (AxPx8760)	Q	-	Wh/year

2.2.5. Characteristics and Properties

The thermal conductivity, density, thickness, costs and temperature can be easily compared, because all insulation material suppliers use the same units. The units of the remaining characteristics and properties can vary by material and by supplier.

The material costs can be influenced by discount, construction and transport costs. In case of a competitive market, discounts increase to 50%. The costs can include construction labour costs, in case of in-situ sprayed materials for example. Insulation material is mainly transporting air volume, which has an impact on its transport costs.

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The thermal conductivity is an important but not the only determining criterion to select a seasonal storage insulation material. Especially the temperature resistance and compression strength are important criteria in case of storage temperatures up to 90 ˚C, and in case that a robust insulation layer is required. A well-known and well available insulation material is polyurethane (PU), or its equivalent polyisocyanurate (PIR), which are applied as an in-situ sprayed layer, or as a prefabricated board or panel core.

The main properties and units are as follow:

Thermal conductivity, lambda value (λ)	W/m.K
Density, specific gravity	kg/m3
Board thickness, layer thickness (d)	mm
Material costs (including 0% discount)	€/m3
Minimum – maximum temperatures	˚C
Water absorption volume (days)	%
Water vapor diffusion resistance factor (μ)	-
Air permeability	kg/Pa·m·s
Bending strength	N/mm2
Compressive strength	MPa
Tensile strength	MPa
Hardness	IRHD

After the following paragraph there is a table made after contacting with many suppliers in order to have some references of different insulation materials. For the blank cells no available value has been found.

Concerning costs they usually depend on local discounts, some average costs are 120-150€/m^3 for Wools, 200-325€/m^3 for PU and 400-500€/m^3 for PE.

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	Thermal Conductivity (λ)	Density	Thickness (d)	Min-Max T°	Water Absorption	Vapor Diffusion Resistance Factor (μ)	Bending Strength	Compressive Strength	Tensile Strength
	W/m.K	kg/m3	mm	˚C	%	-	N/mm2	N/mm2	N/mm2
Aerogel	0.013-0,014	142	5-10	-40-200					
Calcium Carbonate	0,076	640-670		2-427					
Cellular Concrete	0,076-0,112	250-400	150-500				0,13-0,14	0,85-2	0,13-0,24
Cellular Concrete in-situ sprayed	0,122-0,547	600-1.600					0,57-2,33	3,3-12,2	
Cellular Glass	0,038-0,050	115-135	30-130	-260-430	0		0,45-0,53	1,57	
Cellulose Fibre	0,035-0,046	35-100	40-200		35	1-2			
Clay	0,100-0,150	400-550			2-9	45-180	0,98-1,37	1,18-2,94	
Cork	0,037-0,055	140		<100				1	
EPS	0,030-0,045	15-35	10-120	-100-70	3,3-5,0	20-90	0,19-0,57	0,02-0,06	0,20-0,52
XPS	0,025-0,037	25-45	20-120	-50-75	0,11-0,26		0,40-1,00	0,05-0,16	
Glass Fibre in-situ Sprayed	0,035	42-48	20-120	750	0				
Mineral Wool (glass)	0,030-0,036		50-100			1,2			
Mineral Wool (Stone)	0,034-0,040		45-120	<250		1,3			
Perlite	0,040-0,051	35-60		-240-1.400					
Phenolic Foam	0,020-0,023	37	20-159	40-120				150	
Polyethylene (PE)	0,035-0,036	21-40	5-38	-80-100	0,05-0,80	2.500			
Polyisocyanurate (PIR)	0,022-0,028	33-37	80-350	-120-120	<2		>0,15	>0,15	>0,08
Polymethyl metacrylate (PMMA)	0,074-0,082	30	60-120	<90					
Polypropylene (PP)	0,036	20	10-30		<1			0,3	
Polyurethane (PU)	0,023-0,028		<100						
Urea Formaldehyde (UF)	0,026-0,054	10		<100					
Vacuum insulated panel (VIP)	0,004-0,008		60						
Variable conductance insulation (VCI)	0,002-0,007		15						
Vermiculite	0,049	80-100							

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2.3. Membrane Layers

Water vessels for energy storage require water barriers in case that the vessel construction or (inner) thermal insulation is not water proof, or contains open seams. In this chapter of membrane layers the principal membrane characteristics and conditions are described.

Figure: Inner layer of Polish pilot plant of Einstein Project.

The properties of some of the membranes and its tube connections, are compared for storages with the following dimensions and temperatures:

Storage	T curve (ºC-ºC)	L (m)	W (m)	H (m)	Volume (m3)	Surface (m2)
Cool (C)	6-16	2.9	2.9	1.9	16	39
Heat (H)	40-90	2.9	2.9	5.0	42	75

2.3.1. Polymer Resins

Geomembranes include a polymer resin, and various additives such as antioxidants, plasticizers, fillers, carbon black, and lubricants. Heat storage appropriate polymer resins are:

- Ethylene propylene diene monomer (EPDM)
- Polychloroprene or chloroprene rubber (CR)
- Polyethylene (PE)
- Polyester (PES)
- Polypropylene (PP)
- Polyvinyl chloride (PVC)

Geomembranes formulations depend on its application such as landfill liners for example. Compared to these applications, seasonal thermal storages, for hot potable water for example, mainly operate within slightly higher temperature areas.

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Due to its temperature resistance, EPDM is a proven and experienced membrane resin, compared to PE, PP and PVC, and its additives. More expensive EPDM alternatives are some Polyurethanes (PU) with an above 100˚C temperature resistance, and polychloroprene or chloroprene rubber (CR) with an up to 120˚C temperature resistance.

Bitumen roof layers, such as ethylene copolymer bitumen (ECB), are applied in-situ with burners and therefore cannot be fitted in enclosed spaces. Bitumen roof layers, such as atactic polypropylene (APP), require a stable subsurface and are precautionary executed in two layers in case of potable water basin applications.

2.3.2. Membrane Surface

The subsurface carrying the membrane, such as a storage construction wall, or an inner thermal insulation layer, should fully support the membrane to avoid its cracking.

In case of an EPDM membrane for example, a study says that any gap or slit in the subsurface should be smaller than twice the membrane thickness. In case of an EPDM membrane a polyester fiber fleece, that is glued on the membrane, provides extra protection in case of larger gaps or slits in the subsurface.

2.3.3. Membrane Connection

In case of (thermal) water storage applications the water tightness of the membrane connection of the different membrane linings is an essential element for its robustness.

Membranes with DSM's EPDM, carbon, and other additives (depending on the membrane supplier) can be welded (melted) providing a vulcanized membrane connection. European EPDM membranes contain a linen fabric and can be vulcanized. American EPDM membranes contain talcum powder (grey membranes) and can only be glued, and cannot be vulcanized.

Vulcanizing EPDM, under pressure and at 200 ˚C, provides a membrane connection which is stronger and more durable than the EPDM membrane itself. The guaranteed lifetime at a 90 ˚C water temperature of a vulcanized membrane connection is more than thirty years.

An EPDM membrane connection which is glued with a primer, which is widely used in the United States, is not suitable. In Sweden, EPDM roofing membranes are in-situ mounted with a patented blow-dried membrane connection. At 90 ˚C this membrane connection has the risk of capillary penetration of water.

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2.3.4. Pipe Connection

Water circulation connections, with a thermal storage for example, require metal pipe penetrations through the membrane. These pipe penetrations have to remain watertight at 90˚C temperature for fifty years. Pipe penetrations are carried out by means of a mouth, whether or not in combination with a metal tube, or a metal or a stainless-steel band clamp.

The 100 ˚C temperature resistance of a metal pipe penetration through an EPDM bag is tested during a week, which will be used for geothermal storage at a 80 to 90˚C water temperature in four 1,000 m3 EPDM bags three kilometre underground for example.

A pipe penetration is manufactured by punching a gap in an EPDM membrane with a diameter equal to one third of the pipe diameter. By pressing a tube in the gap an EPDM mouth is formed. Backroll of the mouth, applying kit under the mouth, and unroll the mouth, creates a mouth sealing with a lifetime of fifty years.

Another pipe penetration is manufactured by punching a gap in an EPDM membrane with a diameter equal to two third of the pipe diameter. By pressing a tube in the gap an EPDM mouth is formed.

A supplier manufactures pipe penetrations in EPDM expansion vessels with a 1 to 10 m3 volume.

A supplier manufactures pipe penetrations through EPDM membranes by forming a mouth which is sealed with a metal band clamp. A stainless steel band clamp guarantees a lifetime of fifty years.

Another supplier manufactures a pipe penetration for flexible containers which at the inside an outside are provided with a polyamide flag. The pipe is connected to the double flag by a screwed or a glued connection.

2.3.5. Water Expansion

Heat storage in water tanks requires an expansion volume. The water storage volume expands in a 50 to 90 ˚C temperature curve 2,35% from 1012,07 to 1035,90 dm^3/kgton, and in a 70 to 90 ˚C temperature curve 1,29% from 1022.71 to 1035,90 dm^3/kgton.

In the table below, water specific weight and volume at atmospheric pressure are exposed:

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˚C	kg/m3˚C	kg/m3	dm3/kgton˚C	dm3/kgton
0		999,87		1000,13
10	0,08	999,73	0,08	1000,27
20	0,20	998,23	0,20	1001,77
30	0,30	995,68	0,30	1004,34
40	0,38	992,25	0,38	1007,81
50	0,45	988,07	0,45	1012,07
60	0,51	983,23	0,53	1017,06
70	0,57	977,79	0,59	1022,71
80	0,62	971,82	0,66	1029,00
90	0,67	965,34	0,72	1035,90
100	0,72	958,38	0,79	1043,43

The membrane top, or membrane ceiling, can be used for expansion by sinking downwards and rising upwards, whereby the membrane gets free from the above subsurface.

In case that the weight of the membrane top or ceiling causes too much pressure in the water, floating bodies such as air-filled balls in the water, or air-filled tubes in the membrane, can support the membrane.

The water expansion can be provided by an EPDM air bag in the upper part of the storage, which sucks up outdoor air in case that the storage water cools down.

An expansion vessel can be filled with nitrogen to avoid corrosion in case of leakage. An alternative is a tube from the storage bottom to outside of the storage top to evacuate expansion water.

Finally, a nitrogen blanket above the water surface in the storage can serve as an expansion space.

2.3.6. Membrane Materials Characteristics

a) Ethylen propylen diene monomer (EPDM)

EPDM has good resistance to the ultraviolet portion of sunlight, and is formulated by customers into a recipe in which overall three equal volume parts of EPDM, carbon, and other substances are processed, they are even further processed by customers. Some of their applications are roof coverings and windows profiles.

The EPDM membrane recipe, in particular the additives, determine the water temperature resistance. Some EPDM roofing membrane recipes can have a lifespan of 30 years at a 90 ˚C water temperature and its cost is around 20-30€/m^2.

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b) Polyethylene (PE)

Polyethylene geotextiles and geomembranes in soil are usually used as a stabilizing network, and as a waterproof layer.

A low-density polyethylene (LDPE) 1 mm membrane with a 10 year warranty, withstanding 85 ˚C, costs 2,50 to 3,50 euro/m^2. The same material including a double membrane connection, with the possibility for compressed air control, costs around 5 euro/m^2.

Low-density and high-density polyethylene (LDPE/HDPE) membranes can, for a short period, withstand temperatures from 60ºC to 90ºC. Water-retaining membranes of polyethylene (PE) are forming along at 50 to 85 ºC.

c) Polyester (PES)

PES can have an up to 110˚C water temperature resistance, and is a considerable alternative for EPDM. The cost per m^2 is around 20-30€.

d) Polyvinyl Chloride (PVC)

Polyvinyl chloride (PVC) membrane is usually used for swimming pools because of the chlorine resistance, and for ponds. The plasticizers in the membrane formulation reduce the lifetime at higher temperatures so that the material is less suitable for hot storage vessels.

Some PVC membranes can, for a short period, withstand temperatures of 85˚C.

e) Characteristic's resume table

In the table below some characteristics are shown with some supplier's references.

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	EPDM	PE	PES	PVC
Thermal conductivity, lambda value (λ)	0,17 W/mK	-	-	-
Density, specific gravity	1,2 kg/cm2	-	1.017±2 g/m2	1,22 g/cm3
Board thickness, layer thickness (d)	1,2 - 1,5 mm	-	0,75-1 mm	0,27 - 0,29 mm
Material costs	18-28 €/m2	-	23-28 €/m2	-
Minimum – maximum temperatures	-65 - 100 °C	-	-34 - 110 °C	<118 °C
Water absorption volume (days)	-	-	0,025 -0,14 kg/m2	-
Water vapor diffusion resistance factor (μ)	75	-	-	-
Tensile strength	>8 MPa	-	-	>17 N/mm2
Hardness	58±5 °Shore A	-	-	-

2.4. Einstein's Construction Project

As a construction example, the Einstein project, a ring from EPS sheets was made around the foundation of the Polish Pilot Plant to avoid the occurring of thermal bridges in places where the foundation may be exposed to the environmental conditions. The most important layers are EPDM liner and thermal insulation. The EPDM liner is screwed to supporting structure made from steel plates in sizes 1,2m x 2,5m. Between EPDM and supporting structure PUR sheets are applied. The role of PUR sheets is to protect the EPDM against mechanical damage. Wall construction is as follows:

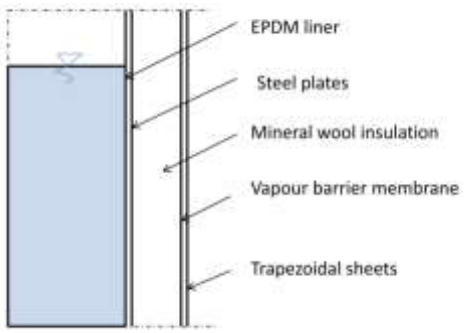

Figure: Wall Construction.

Mineral wool sheets were used as insulation material. The thickness of wall insulation is 70cm. Heat transfer to the top is recognized as one of the greatest path of heat losses from STES. In Polish EINSTEIN Demonstration Plant, STES is insulated on the top with PIR sandwich panels and EPS plates. The total thickness of roof insulation is 60 cm. Insulation layer is protected against outside condition by vapour barrier membrane. Multi-layered roof is supported on steel beams, which are supported on the wall.

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Figure: Wall Construction

For above ground operations, as in FP7 Einstein, where the water table was problematic, the following construction phase was carried out. The ground level foundation was installed as illustrated below.

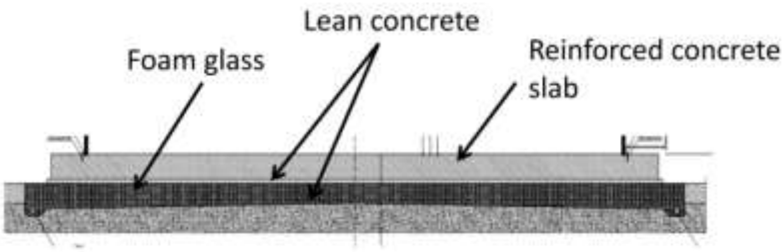

Figure: STES Foundation

For the Bilbao Pilot Plant, a modular construction of a 180m3 double independent tank was made, with an inner Ø6m tank and an outer Ø7,1m tank. For the insulation a 0,45m layer of expended clay granulates was installed at the bottom and the lateral insulation was made of new PUR recycled granulates.

Figure: Einstein's Bilbao STES insulation.

3. Building Integration

3.1. Tank Site Accessibility

Heat storage, especially seasonal storage, requires a relative large volume compared to the dimensions of a building. Even in the case of a single house, the seasonal storage volume has a size of some cubic meters at least.

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Besides the size of the indoor space, especially the accessibility to the building site and this indoor space could limit the storage volume. For this reason the following tank types are distinguished:

- Modular tanks
- Monolith tanks

The modular tanks are assembled by parts which can pass a doorway for example. The seam sealing at the modular tank part connections need special attention. An inner membrane is an alternative. Modular concepts are ideal for existing building stock where spaces may be at a premium because of their very flexible in design, ease of installation, good insulations

The heat losses of the seasonal storage are also an important condition for the system design and its required building integration. In case of underground or rooftop locations these heat losses are less easy to manage and control. A foundation or parking for example could require ventilation, whereby heat losses flow away.

Local legislation such as environmental legislation on soil pollution, or on groundwater protection, for example can prohibit underground storage constructions. The same applies for rooftop storage constructions, such as civil engineering legislation due to the storage weight, and visual impact legislation due to the storage aesthetic or storage height or volume.

3.2. Tank Construction Materials

Modular and monolith tanks are constructed with various materials. On the water side, or inner side, of the tank the following four materials - some with reinforcement - are distinguished:

- Concrete tank
- Metal tank
- Plastic tank
- Wood tank

Some suppliers offer a hybrid solution with an inner metal tank and an outside plastic tank for example.

3.3. Tank Production Process

The production costs can be reduced by prefabrication. In case of a cylindrical tank, the tank can be a part of a pipe and its (endless) pipe production process. For the concrete,

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metal, plastic and wooden monolith tanks the following production processes are distinguished:

- Pipe production: tube production by extrusion or wrapping for example.
- Tank production: prefabrication by hand lay-up on a mould for example.

3.4. Tank Water Expansion

The water expansion in the tank can be controlled by an overflow or a membrane for example. An experimental solution that is using the tank itself as an expansion element is based on Integrated Geodesic Winding (IGW) with the advantage, with respect to cylinders, that all the fibres in the composite are charged for 100%.

This principle has been developed for an inflatable aircraft cabin, which is at a greater height by a pressure of 0.4 bar (with a calculated value of 0.8 bar) to expand and thereby is allowed to widen but may not extend. Because of the fibre structure and fibre direction the expansion can be collected only in the width, while the length remains unchanged.

3.5. Modular Tanks

In the following points different type of modular tanks are described, some of them using real cases examples:

3.5.1. Concrete Modular Tanks

a) Concrete Shell Element Tank

Curved or straight walls used for cylindrical tanks or silos can be supplied by various concrete shell element manufacturers, and are applied for tunnel walls or tubular underpasses, or can be used as a heat exchanger for example.

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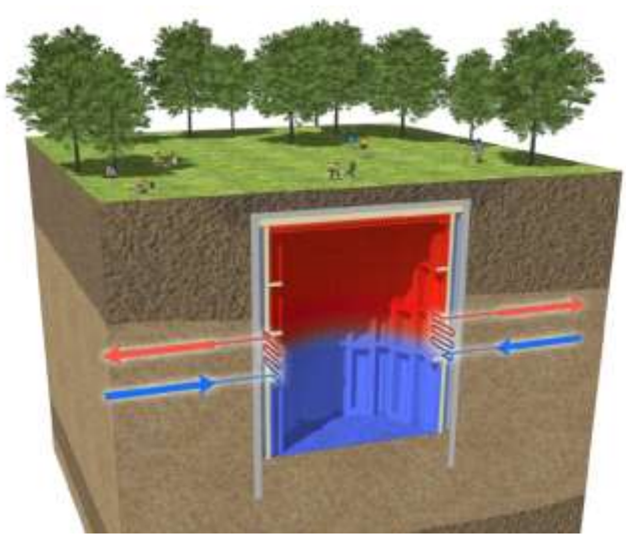

Figure: Concrete Shell Element Tank (Source: De Groot, Ecovat)

b) Concrete Ring Element Tank

Concrete ring elements with a 3,000 mm diameter, a 500 mm height, and 150 mm wall thickness can be covered with a conical cover element on top, and are offered as monolith tanks including these elements.

Figure: Concrete ring Element Tank (Source: Nering Bōgel, NeBo afvalwateropslagtank)

3.5.2. Metal Modular Tanks

a) Metal Space Frame Tank

An underground rectangular storage tank innovation, with an internal metal space frame triangle construction, can deal with wheel pressures of 5 tons per wheel. The tank can be encapsulated by hand lay-up PU, and the top can be covered by EPS.

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Figure: Subsurface Solar Thermal Energy Storage (Source: HoCoSto)

b) Steel Ring Element Tank

A well-known modular steel ring element tank is a Sprinkler tank. A Sprinkler tank can be sealed inside with an EPDM membrane, and all connections for pipes are connected on top of the storage so that the EPDM membrane is only pierced there.

3.5.3. Plastic Modular Tanks

a) Polypropylene (PP) Casette Tank

A box of 540 x 1150 x 3000 mm (1,000 litre) is assembled of polypropylene (PP) shell parts with EPS insulation and a reinforced PVC water bag, to store heat in a crawl space under the ground floor, having a limited height of about 60 cm for example.

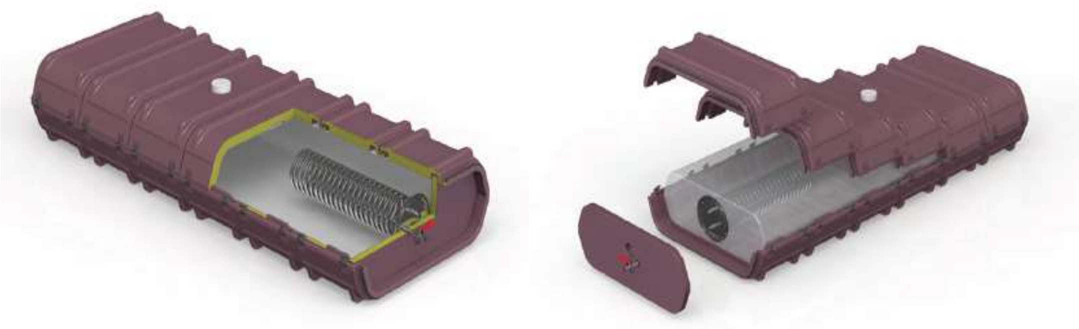

Figure: PU Casette Tank (Source: Compaan, Flexsaver)

Thermal storage units can consist of individual segments with intermediate floors. The construction of segments and perforated intermediate floors absorbs the water pressure and at the same time improves the layering behavior of the reservoir.

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Figure: Intermediate floors (Source: Enersolve, Módulo Thermalspeicher)

b) Polyurethane (PU) Block Wall Tank

A storage is constructed with stacked PU 150 mm foam tank wall blocks. The pressureless system has a central heating layering column with 850 mm diameter for separation of different temperature layers.

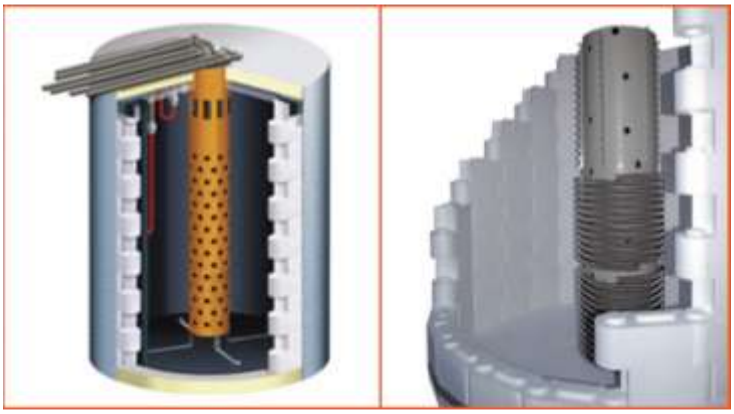

Figure: Futus Speicher (Source: Futus)

c) Polyurethane (PU) Sandwich Panel Tank

Storage containers can be constructed from a steel frame which is filled with polyurethane (PU) sandwich panels. Due to its build-up element construction is mainly suitable for construction in existing indoor spaces, and withstands water pressure up to 3.5 m water column height.

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Figure: PU Storage Container (Source: FSAVE, FLEXSAVE Wärmepufferspeicher)

An alternative is a fibre-reinforced polyester tank with a sandwich wall which is delivered rolled up, and is containing a 100 mm pressure-resistant insulating material. Unrolled the cylindrical tank wall is closed with a bottom and top element which both can be divided into halves.

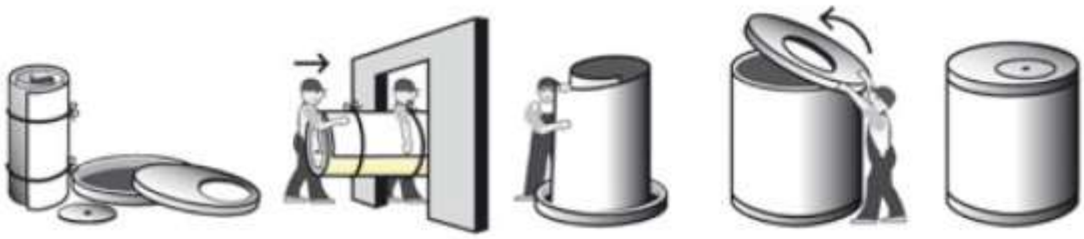

Figure : T400's construction technique (Source: Haase, Haase-Wärmespeicher)

As an example, Haase hot water tanks of the T 400 series consist of an inner tank made of high-quality GRP (glass-fibre reinforced plastics) and a thermal insulation that is in turn protected to the outside by a GRP jacket. Depending on the needs the T 400 is provided with an internal corrugated stainless steel heat exchanger or prepared for external heat exchangers. Capacities of up to 40,000 litres are possible. Below ground versions are also available.

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d) Three-dimensional Woven Panel Tank

A new development is a three-dimensional woven two-wall material whose two surfaces are inter-connected by a variety of distance-retaining pile yarns. The material for tank applications is still under investigation.

3.5.4. Wooden Modular Tank

a) Ribs Reinforced Solid Wood Tank

A solid wood storage vessel has in case of an octagonal shape a 20 cm wall thickness. An alternative is to stabilize the wall, and reduce its thickness, by horizontal wooden ribs. The tanks can have a thermal insulation and water-retaining layer at the inside.

3.6. Monolith Tanks

In the following points different type of monolith tanks are described:

3.6.1. Concrete Monolith Tanks

a) Concrete Pipe

A sewer pipe with 3.600 mm inner and 4.400 mm outer diameter, 3.000 mm length, and 400 mm wall thickness, can be used as a horizontal or vertical storage cylinder.

b) Concrete Tank

A well-known concrete monolith tank is a submersible basement which is used as an underground cellar or swimming pool for example. The prefabricated basement caisson is transported and placed on site in a horizontal position.

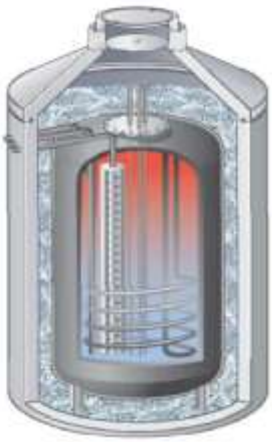

Figure: Mall, Mall-Pufferspeicher ThermoSol

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3.6.2. Metal Monolith Tanks

a) Helically Corrugated Steel Pipe

Helically corrugated steel pipes, made out of lock seamed galvanized steel strip, have a maximum diameter of 2.800 mm, a steel strip thickness of 1'25, 1'9, 2'7 or 3'3mm, and a maximum length of 12 m.

Figure: Corrugated Steel Pipes (Source:BCT, SPIRoso)

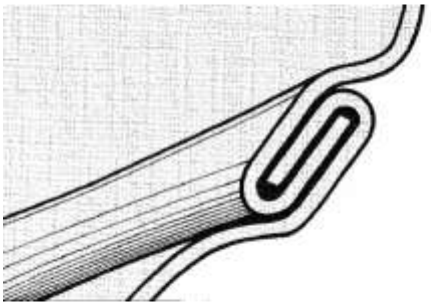

Figure: Lock seam (Source: BCT, SPIRosol)

b) Steel or Stainless Steel Tank (insulated)

Steel tanks are offered for all kind of applications, such as including a copper or flat tube heat exchanger, an EPDM sealing, an internal boiler, and insulation layers such EPS foam covered with aluminium foil, aluminium coated glass wool mats, and PU foam with a glass fibre reinforced polyester encapsulation.

Steel tanks for water based seasonal thermal energy storage are typically welded and can be inserted into the building structure during construction. Thus heat loss can benefit the house in winter but may be problematical in summer, depending on levels of insulation. Alternatively they can be retrofitted if there is sufficient space.

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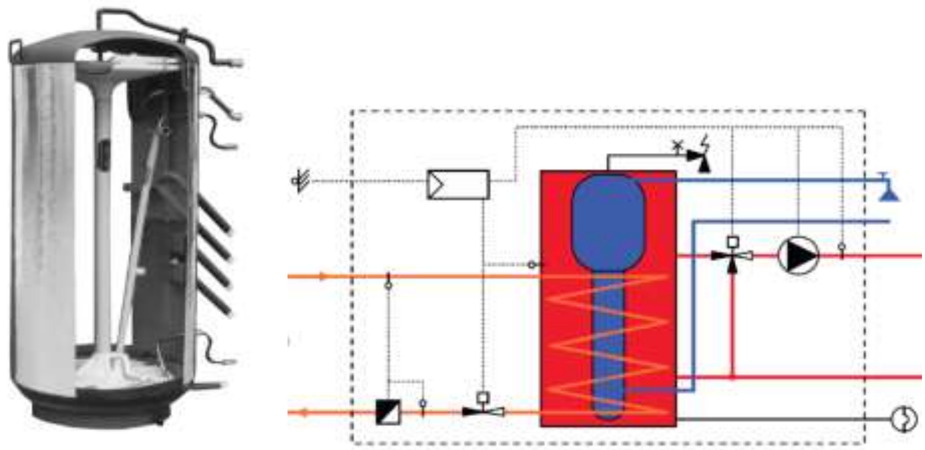

Figures: Steel Tank Design (Source: Haase, SOLUS II Solar-Kombispeicher, Jenni, Swiss Solartank)

3.6.3. Plastic Monolith Tanks

a) Ethylene Chlorotrifluorethylene (ECTFE) Pipe

Due to its temperature resistance ECTFE is a suitable material for heat storage vessels, and ECTFE pipes - especially the available diameters - are under investigation.

b) Fibre Reinforced Plastic (FRP) Tank

Many animal feed silos are made of FRP such as glass fibre reinforced polyester (GFRP). GFRP gives at the final recycle phase a glass residue in the incinerator. Cellulose and synthetic fibres are an alternative, but still in development stage. Especially the cellulose fibre moisture sensitivity is a major concern in case of applications in a humid environment.

Figure: Haase-Kugeltank (Source: Haase)

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c) Glass Reinforced Epoxy (GRE) Pipe

GRE pipes have a maximum diameter of 1.800 mm, and 1.200 mm for bulk production, and are used for district heating systems with 95 to 100 ˚C temperatures.

d) Integrated Geodesic Winding (IGW) Tank

The IGW invention is the result of a mathematical calculation with the advantage, with respect to cylinders, that all the fibres in the composite are charged for 100%. The IGW principle can be used for an inflatable aircraft cabin, which, due to lower pressure at greater height, will expand, and is allowed to widen but may not extend.

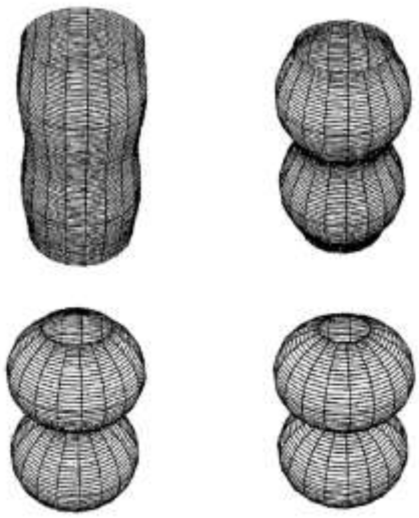

Figure : Pressurisable Structures (Source: TU Delft)

e) Polyethylene (PE) Pipe

A German polyethylene (PE) wrapped pipe has an inner and outer pipe with a 5 mm thickness each, and in between a 20 to 30 mm cavity. A 50 m3 PE tank, with a 3.500 mm diameter and a 8.000 mm height, costs 17.500€. The PE temperature resistance is 40 to 45 ˚C. *(Source: Beuker)*

f) Polyvinylidene Fluoride (PVDF) pipe

Due to its temperature resistance PVDF is a suitable material for heat storage vessels, and ECTFE pipes - especially the available diameters - are under investigation.

3.6.4. Wooden Monolith Tank

a) Tensioning straps reinforced wooden tank

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Wooden tanks, such as salt deposit silos today and potatoes storage boxes in the past, are reinforced by outside wooden ribs or metal straps to hold the pressure on the tank wall. This pressure on the tank wall increases from the wall upper side to the wall underside, which is visible by its increasing ribs or strips density.

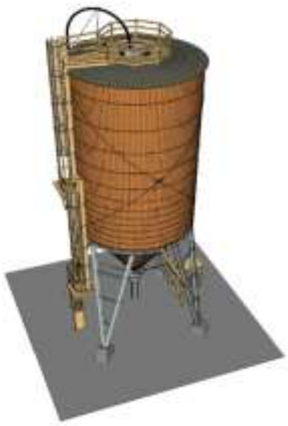

Figure: Wooden round silo 400 m3 (Source: Blumer-Lehmann)

3.7. Tank Transport Dimensions

Monolith tank dimensions are influenced by both European legislation and transport costs. European legislation prescribes the public road transport maximum width, length, height, weight and axle load of a vehicle, and, in this case, traction-trailer combination. Exceptional transport requires extra (police) escort costs for transport control or to warn other road users.

European legislation prescribes in case of transport by a traction-trailer combination (3+2 or 3+3 axles with air suspension) the dimensions for three exemption situations:

Exemption	m width	m length	m height	kg weight	kg axle load
None	2,55	16,50	4,00	44.000	10.000
Long-term	3,50	27,50	4,15	100.000	12.000
Incidental	4,50	60,00	4,50	100.000	12.000

Another case in Germany is to transport heat to a school over a distance of 10 km from a biomass power plant. Heat demand there is on average about 1850 kWh each year that is covered by heat supply from a local oil boiler with an energy-utilization efficiency of 85%. After modification of the existing system, transported heat was mainly responsible for heat demand, and oil boilers were retained as a backup for the peak demand. The heat transport technology was from the TransHeat Company, and sodium acetate trihydrate served as the storage material in this application. This material has a phase-change temperature = 58°C.

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Parameters	Value	
Container dimension (m)	6 × 2.5 × 2.5	
Weight of sodium salt (t)	26	
Heat storage capacity (100–58°C) (MWh)	2.93	
Maximum storage temperature (°C)	100	
Maximum load power (MW)	1	
Average heat loss (k*A) (kW/K)	0.0105	
Daily heat lost (Q_{sp}: 2.93 MW, $T_{outside}$ = 10°C) (kW/d)	23	
	Sodium Acetate Trihydrate	Erythritol
Latent heat of fusion (kJ/kg)	264	340
Melting point (°C)	58	118
Supply temperature (°C)	50	110
Heat storage capacity (MWh)	1.96	2.29
Charging velocity (MW)	Max 1.0	
Discharging velocity (MW)	Max 0.5	
CO_2 reduction effect (kg/container)	478	558

Figure: TransHeat Concept

There is emerging data on transportation concepts which may apply for commercial applications.

Figure: Transportable Heat Concept

4. Borehole and Aquifer Storage

4.1. Storage Systems

Doing again a quick review of D2.1, in borehole thermal energy storage (BTES) heat is stored directly into the ground. BTES do not have an exactly separated storage volume and the heat is transferred to the underground by means of conductive flow from a number of closely spaced boreholes.

The geological formations required are that of rock or water saturated soils with zero or only very low natural groundwater flow. The ground should have high thermal capacity and low permeability. The depths are typically from 30 to 200 m and the heat is directly stored in the water-saturated soil. The u-pipes, also called ducts, are inserted into vertical boreholes to build a huge heat exchanger leading to a heat storage capacity of the ground of between 15 and 30 kWh/m3.

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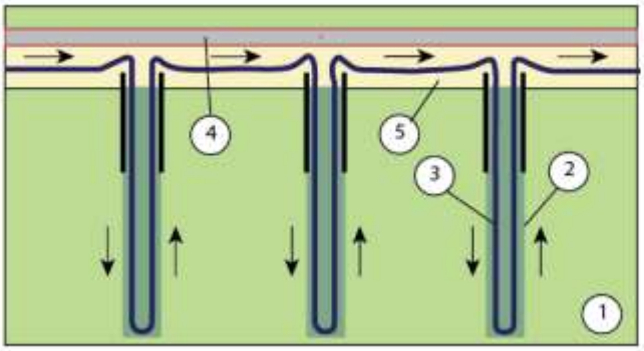

Figure: Borehole thermal energy storage (BTES) system.
[1]soil; [2] grouting; [3] borehole heat exchanger; [4] covering layer; [5] heat insulation (Source: D2.1)

On the other hand, aquifer thermal energy storage (ATES) require to build two reversible wells (or group of wells) one will be the cold sink and the other the warm. During warm season cold water is removed from the cold sink, heated by the solar energy or other energy sources and sent to the hot sink. During cold season the cycle is reversed; the water is removed from the hot sink, cooled by the heat pumps (or heat exchanger) and sent to the cold sink.

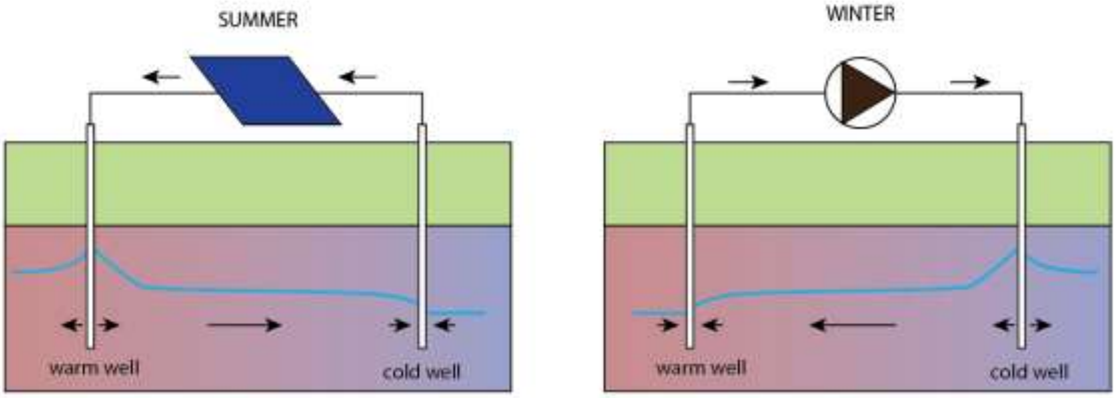

Figure: Operation of ATES (Source D2.1)

The aquifer must have high porosity, ground water and high hydraulic conductivity, small flow rate, and above and below enclosed with leak-proof layers. They have a heat storage capacity of between 30 and 40 kWh/m^3.

4.2. Soil Description and Analysis

Soil properties are variable from one site to another site in terms of thermal conductivity, heat capacity, density, water content, porosity, etc. Hence, soil cannot be generalised as one invariable parameter.

However, conducting soil analysis for every site does not often make economic sense. Thus, while soil properties do vary from site to site, for the use in most practical applications like preliminary designs or long term simulations soil can be analysed as homogenous with constant thermal and physical properties.

The sections below this chapter will look into an analysis of the soils properties.

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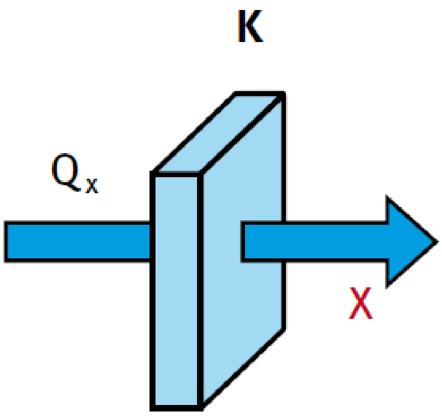
4.2.1. Thermal Conductivity and Capacity

The efficiency of the Thermal Energy Storage System (TESS) is influenced by the conductivity of the soil. Thermal conductivity of each material indicates its capacity to conduct heat and it is generally expressed in W/mºC or W/mK.

$$Q_x = -kA\frac{dT}{dx}$$



Where k is the thermal conductivity, Q_x is the heat diffused, A is the area, and dT/dx is the temperature gradient.

The accurate thermal conductivity for applications in ground heat exchangers can be also determined through soil surveys. The most common test and widely accepted is the thermal response test which consists of the injection of a constant heat flux and sense the temperature variation in a determined distance (radial) and depth. Through these results the accurate average thermal conductivity of the soil can be determined.

High conductivity soil is the best performer for the renewable heat system. For practical purposes, most soils have a thermal conductivity between 1,2 to 3,5 W/mK, and can be classified as: low conductivity soils (less than 1,5 W/mK), medium conductivity soils (from 1,5 to 3 W/mK) and high conductivity soils (more than 3 W/mK).

The graphic below summarizes the thermal conductivity for some soil types:

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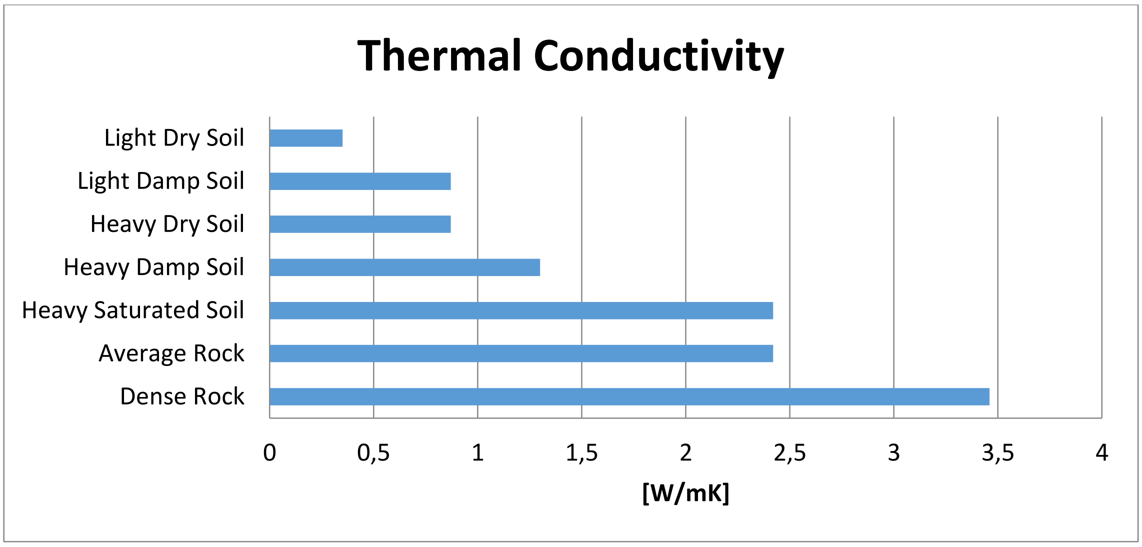

Furthermore, thermal capacity of the soil is the heat that a determinate volume can store as its temperature raises and can be calculated with the following formula:

$$C = \frac{dQ}{dT}$$

Where C is the thermal capacity and dQ the heat needed to raise temperature dT.

In Appendix 1 there is a table with approximate thermal conductivity and capacity values for different materials from IDAE. In the UK context, the British Guide MCS MIS 3005 (Microgeneration Certification Scheme, Microgeneration Installation Standard) provides some look up tables to get the thermal conductivity and heat capacity of the soil according to their composition (dry clay, most clay, sand, etc.).

4.2.2. Energy Density

The thermal energy density of the soil is directly related to its thermal properties: specific heat and density. For example, changes in the conditions of the soil, for example wet vs. dry and hot vs. cold, have an effect on its energy density.

The formula for calculating Energy density in J/m3 is:

$$Energy\ density\left(\frac{J}{m^3}\right) = \rho \times Cp \times \Delta T$$

Where ρ is the density of soil in kg/m3, Cp is the specific heat of the soil in J/kg K and ΔT are the difference between the initial and final temperature of the soil.

4.2.3. Diffusivity

Thermal diffusivity is defined as the ratio between the thermal conduction capacity of the soil and its thermal capacity, measured in m^2/s. The idea gives some approximate values of soil diffusivity from $0{,}36 \cdot 10^{-6}$ to $1{,}08 \cdot 10^{-6}$ m^2/s depending in if the soil is dry or wet.

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4.3. Field Configuration

Piping system configurations can be closed or open:

4.3.1. Closed Systems

Most common used systems for BTES with heat pump are closed systems, which consist in a fluid circulating into an exchange buried piping system. This system allows taking profit of the external levels of the surface when the permeability of the soil does not permit obtain heat from the groundwater.

Closed system can be horizontal and vertical:

a) Horizontal Closed Systems

There are multiple options and they are the easiest ones to install, otherwise they should adapt to the space limitation. Heat comes from sun irradiation.

In the figures below different horizontal closed systems are represented (Figure's source: IDAE Geotermia):

Serial Collector

Parallel Collector

Trench Pipe

Slinky Collector

Svec Collector

Trench Collector

The installation consists in excavate the outer layers (0,9-1,0m minimum), install the collectors and cover them with the excavated soil. The pipes are generally made of polyethylene with diameters from 25 to 40mmm.

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Figure: Slinky Horizontal (Source:IDAE)

b) Vertical Closed Systems

Heat is charged or discharged by vertical borehole heat exchangers which are installed into a depth of 30–200 m below ground surface. At charging, the flow direction is from the centre to the boundaries of the store to obtain high temperatures in the centre and lower ones at the boundaries of the store. At discharging the flow direction is reversed. The boreholes have diameters of about 0,1 m – 0,2 m and require a horizontal gap of 1,5 m – 3 m between each of them.

Vertical System

Figure: Geothermal borehole (Source: D2.1)

The collector pipes can be installed in U form or coaxial:

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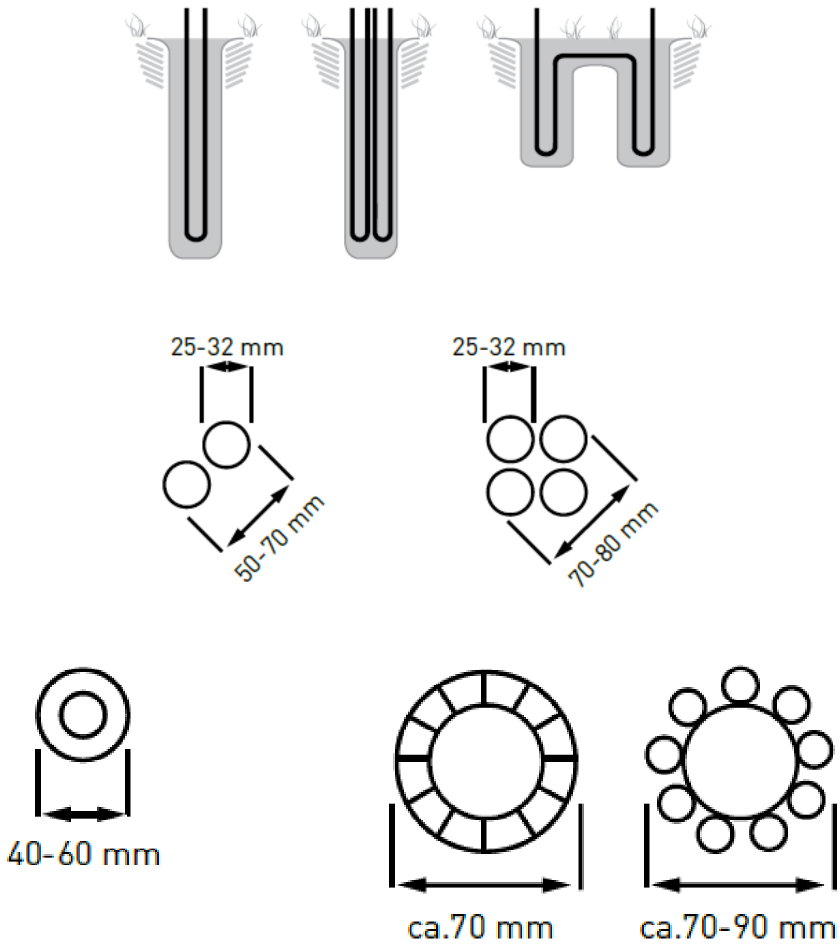

Figures: U and Coaxial section collectors (Source: IDAE Geotermia)

Finally, this type of store can be insulated at the top. It is important to protect this insulation against rainwater. Therefore, a sheet that is waterproof at the top and open to allow vapour diffusion at the bottom is designed for use as the insulating layer. This foil layer has gradient enabling rainwater to drain from it. A drainage layer and soil are put on top of it. Finally, humus is applied, so that the thermal energy store is completely under ground level.

4.3.2. Open Systems

Open systems are a good choice for places with alluvial groundwater presence. Heat comes from the ground water that flows in the subsoil. If there are impervious layers above and below and no or only low natural groundwater flow, they can be used for heat (and cold) storage.

As explained previously, usually two wells are needed, one to extract the ground water and the other to inject it again in the aquifer. Because of the different flow directions both wells have to be equipped with pumps and production and injection pipes.

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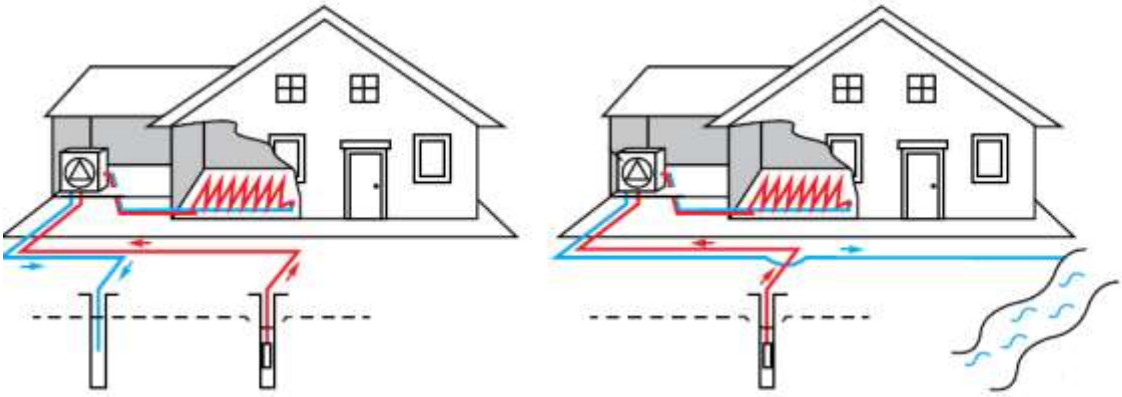

Figure: Open system with heat pump configurations (Source: IDAE Geotermia)

To implement this systems a high permeability of the soil is required in order to obtain the necessary flow of water in a shallow depth and a good quality of water to avoid corrosion and obstruction of the pipe's system.

Those systems are simple, cheap and offer a good performance but their administrative processing is complex.

4.4. Pipework Materials

Due to its inaccessibility once installed all the components required for a borehole heat exchanger network should be of very high quality and durability. The requirement for a long design life span for all the heat exchanger components is very important and should be considered in the material choice during the design of a BTES.

The pipes are generally made of polyethylene, propylene or PVC. According to GSHPA recommendations in the UK, an acceptable pipe material for the ground heat exchanger shall have a slow crack growth resistance, at a pressure of 9,2bar and temperature of 80°C, of greater than 500 hours, e.g. PE100+, PE100RC etc. The manufacturer shall warrant that the pipe is extruded from verifiable virgin grade raw material from a certified producer of PE pipe materials which meet the enhanced technical requirements. Pipe shall be manufactured to outside diameters, wall thickness and respective tolerance.

4.5. Drilling Techniques

The following are some low-cost, appropriate drilling methods which can be used:

- Cable Percussion drilling: This system is used for medium-large diameter and low-medium depth drilling works (up to 60m).

  The action is carried out by cable percussion tools of three main types:

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- Buckets, used in the absence of water.
- Probes or dippers, used in loose or medium compact soils and in the presence of water.
- Chisels, used in compact soils.

The tool should be connected to the free fall winch through a steel rope and is repeatedly raised and dropped to the bottom of the well. After a suitable advancement of the drilling and at regular intervals, the tool is pulled out from the well and the drilled material removed.

Figure: Cable percussion drilling (Source: RSA Geotechnics)

- Hand-auger drilling: This consists of extendable steel rods, rotated by a handle. A number of different steel augers (drill bits) can be attached at the end of the drill rods. The augers are rotated into the ground until they are filled, then lifted out of the borehole to be emptied. Specialized augers can be used for different formations (soil types).

- Rotary-percussion drilling: This method uses a rotary action combined with downward force to grind away the material in which the borehole is being made. Is usually used for depths that do not exceed 150m.

- Rotary drilling with flush: This method employs the rotary drilling action but uses air-mist, polymer foam or water flush to aid coring whilst drilling.

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Figure: Rotary Drilling (Source:hdengineering)

5. Internal Structure

There are many different concepts for internal structure devices in the market in order to heat and maintain the temperature of the tanks. Almost all of them are designed for small storage systems and there is not much experience available for large scale applications, this requires the elaboration of specific studies for every case.

Figure: Different storage systems (Source: Fröling)

5.1. Stratification

Previous research on solar hot water system revealed that thermal stratification can lead to longer operation hours and thus a significantly larger utilisation of solar

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collectors, and thereby a reduction in the use and cost of auxiliary energy. It has been further stated that the heat store of small solar heating systems is the most important component of the system, both from an economy point of view and from a thermal performance point of view. This is further supported by the statement that the storage tank is an important component of the SWH system which plays a major role in dictating the system performance.

Thermal stratification can occur through the combinations of a number of mechanisms. The first of these is heat loss. Water close to thermal bridges such as tank walls, inlet and outlet connections, will lose heat to the surroundings and become cooler. Thermal dynamics due to density differences between hot and cold water, will establish thermal stratification throughout the storage tank.

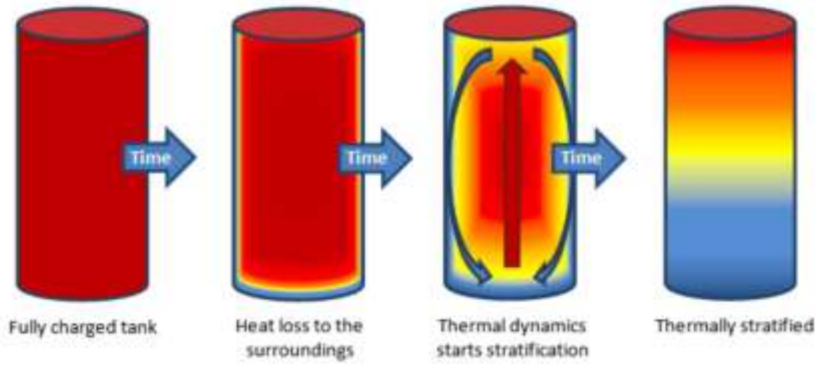

Figure: Hot water tanks can become stratified over time if not disturbed (Source: University of Ulster)

The thermal dynamics for a water storage system for example are defined by:

Density (kg/m3) $\rho = 863 + 1{,}21T - 0.00257T^2$

Dynamic Viscosity (kg/ms) $\mu = 0{,}0007 \left(\frac{T}{315}\right)^{-5.5}$

Thermal Conductivity (W/mK) $\lambda = 0{,}375 + 8{,}84 \cdot 10^{-4}T$

Where T is the temperature (Kelvin).

During charging when using conventional heating (oil, gas, district heating etc.), the water in the tank (top) is never warmer than the water coming from the heat source. Stratification can be kept intact during heating by applying the heated water to the top of the tank, and drawing off the cold water (which is to be heated) from the bottom of the tank.

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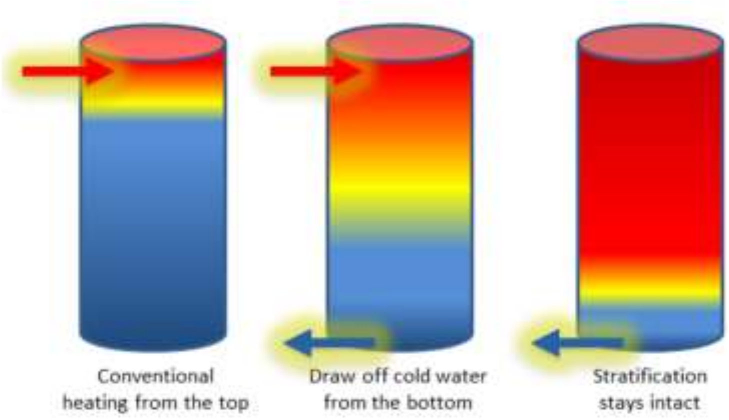

Figure: Stratification is kept intact by heating from the top (Source: University of Ulster)

In small tank systems, stratification can be managed by choosing where to charge and discharge from. This is illustrated by the Ratiotherm's Oskar store using VIP insulation which has numerous charge and discharge points.

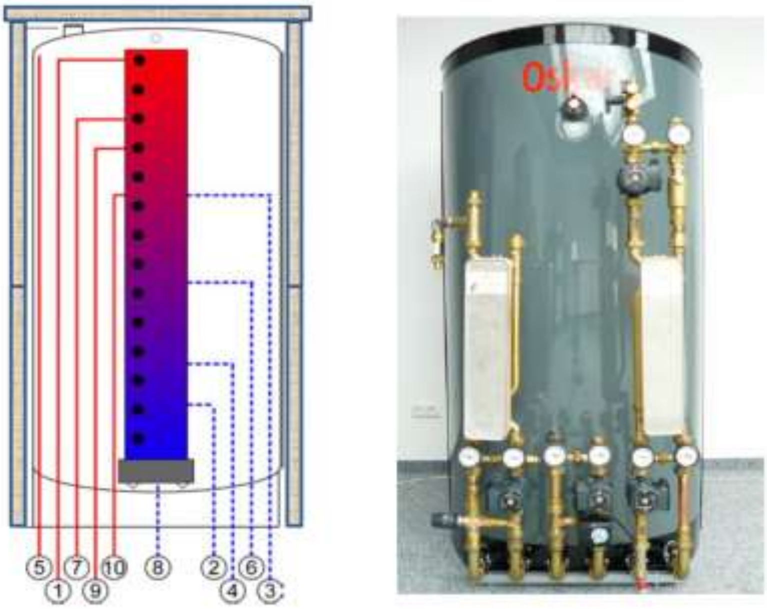

Figure: stratification system of Ratiotherm's Oskar

During discharging and when a tank is stratified, the water is always warmest at the top of the tank. Therefore, when discharging hot water for domestic use or space heating, the draw off is always done from the top part of the tank. Refilling will occur at the bottom of the tank to avoid thermal mixing.

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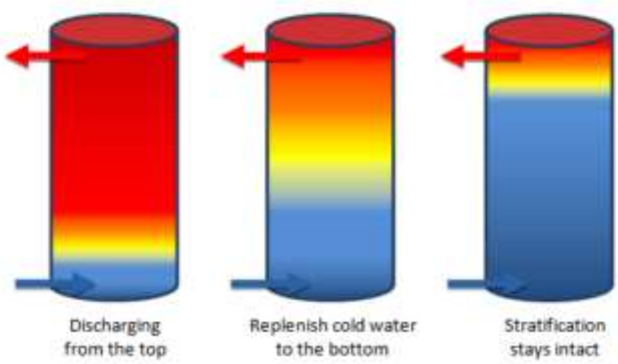

Figure: Stratification is kept intact during discharge (Source: University of Ulster)

There are many factors influencing both the efficiency of a thermal storage system, and the quantitative advantages from obtaining thermal stratification. Some of the factors are as per below:

- Height/ diameter ratio of tank
- Thermal bridges in the top part of the tank
- Tank insulation
- Tank design
- Flow rates
- Stratification enhancers

However, there are a number of significant challenges in building and maintaining thermal stratification in a solar thermal system. Three topics are of most relevance to this are:

- Variable inlet temperatures
- Variable height of a specific thermal layer
- Heating from the bottom of the tank

5.1.1. Variable Inlet Temperature

If water at 20⁰C enters a stratified tank at the top part, this cooler water will push its way downwards towards the bottom of the tank, and the thermal stratification will be disturbed.

If 100⁰C hot water enters a stratified tank at the bottom part, the water will be pushed upwards towards the top the tank, and the thermal stratification will also be disturbed. The challenge is that the thermal layer, appropriate to the inlet water, differs according to the variable inlet temperature as well as the temperature profile inside the tank.

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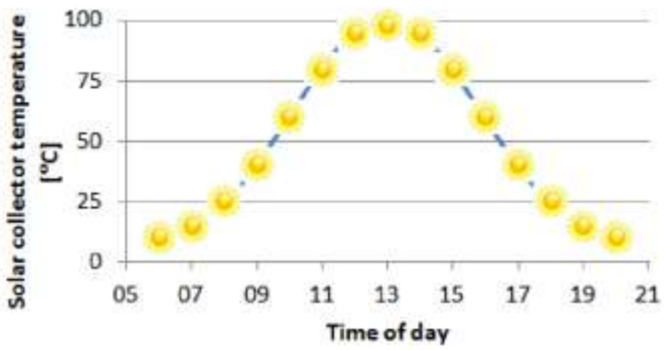

Figure: Why are variable inlet temperatures obtained in solar thermal heating Systems (Source: University of Ulster)

In resume, the temperature stratification is carried out automatically as hot water is less dense and therefore rises. However, to prevent any mixing of the layers, a stratification device can be used for charging in accordance with its temperature. Stratification allows increasing the efficiency of the heat pump and solar collectors.

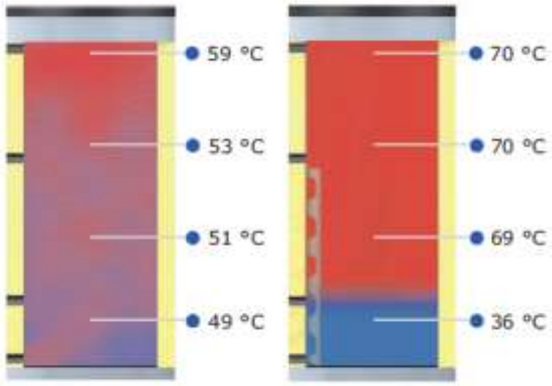

Figure: without stratification system vs with stratification system (Source (Fröling)

Figure: Internal aspect of a big TTES (6,000 m³). Ackermannbogen (Munchen)

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5.1.2. Variable Height

The temperature of the water in these return inlets does not necessarily vary a great deal. However, the temperature profile inside the tank can vary a lot. The appropriate thermal layer for the returning water being at different heights. For example, the return water may be rather stable between 40^{0}C - 50^{0}C and the equivalent thermal layer inside the tank can be close to the bottom or close to the top, depending on how much and how well the energy is stored in the tank.

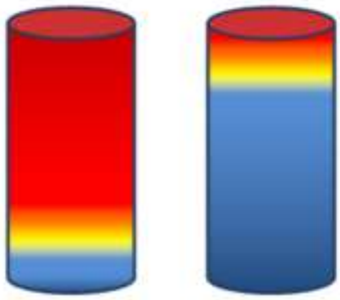

Figure: Temperature-Height variability concept (Source: University of Ulster)

In large storage volumes, for example, charging diffusors are often used in different levels like in the Einstein Project:

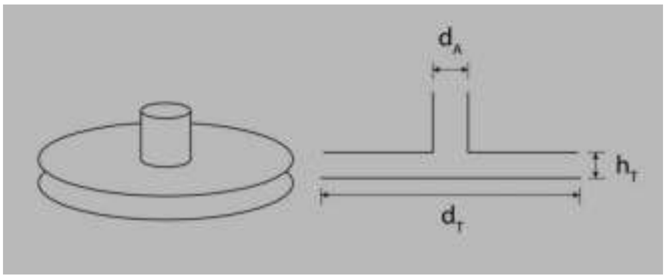

Figure: Charging diffusor (Source: Solites)

Figure: Stratification devices for the Einstein Project

If there is the need to install more than one tank there is the possibility to connect up to 4 tanks (of low height and diameter) using an intelligent stratification system.

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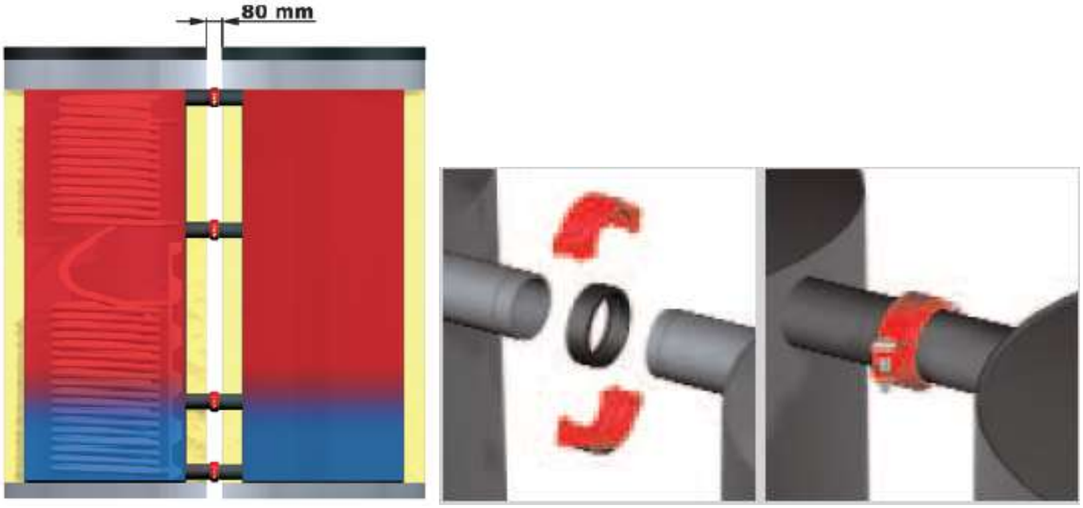

Figure: Connected Stratification tanks (Source: Fröling)

5.1.3. Heating from the Bottom

Many solar storage tanks have a coil heat exchanger installed in the lower part of the tank. When this type of technology heats up a stratified tank, the heated water will be pushed up towards the top the tank, and the thermal stratification will can be disturbed.

Figure: Coil Heating Disturbing Stratification (Source: University of Ulster)

The Richardson number, Ri, the ratio of buoyancy to inertia forces in the storage tank, has been widely used to measure stratification. It is expressed as:

$$Ri = \frac{g\, \beta\, H \left(T_{in} - T_{out}\right)}{U_{in}^2}$$

where β, the compressibility of the storage fluid, is computed at the average temperature in the tank, $T_{av} = (T_{in} + T_0)/2$. Storage tanks with higher *Ri* experience greater stratification.

The Richardson number can also be expressed by using a combination of the Grashof number and Reynolds number,

$$Ri = \frac{Gr}{Re^2}$$

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Typically, the natural convection is negligible when Ri < 0.1, forced convection is negligible when Ri > 10, and neither is negligible when 0.1 < Ri < 10. It may be noted that usually the forced convection is large relative to natural convection except in the case of extremely low forced flow velocities where the Grashof (Gr) number may be given a form of:

$$Gr = \frac{g\,\beta\,(T_s - T_b)\,D^3}{v^2}$$

Where:

g is acceleration due to Earth's gravity

β is the coefficient of thermal expansion (equal to approximately 1/T, for ideal gases)

Ts is the surface temperature

Tb is the bulk temperature

L is the vertical length

D is the diameter

v is the kinematic viscosity.

5.2. Heat Exchangers

Heat exchangers separate different hydraulic circuits. This is useful if, for example, different liquids flow through two circuits or heat exchangers are likewise used between the pressurized pipes and the unpressurized thermal energy stores.

5.2.1. Heat Exchanger Design

The study of heat exchanger design (and heat transfer in general) relies on the calculation of overall heat transfer coefficients. These will be outlined for single phase (i.e. always liquid or always vapour) and two phase (where a change from liquid to vapour or vice versa occurs). The overall heat transfer coefficient of a single phase flow is the Nusselt number which is itself a function of the Reynolds and the Prandtl numbers such that:

$$Nu = \frac{\alpha l}{k}$$

$$Re = \frac{\rho\,u\,l}{v}$$

$$\mathrm{Pr} = \frac{Cv}{k}$$

Where:

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l = characteristic length (m)

ρ = fluid density (kg/m3)

υ = mean velocity (m/s)

C = fluid specific heat capacity (J/kgK)

v = viscosity (Ns/m²)

k = thermal conductivity (W/mK)

α = heat transfer coefficient (W/m²K)

In a channel of uniform cross-section, the Dittus-Boelter expression is acceptable such that:

$$Nu = 0{,}023\ Re^{0.8}\ Pr^{0.4}$$

where the characteristic length is a function of the flow area S and the channel perimeter P such that:

$$l = \frac{4S}{P}$$

Typical heat exchanger geometries utilise the following characteristic lengths (l):

Geometry of flow	l
Tube of i.e. Di	Di
Between plates a distance b apart	2b
Rectangular channel of sides of length a and b	2ab/(a+b)
Tube-in-tube, outer tube id D, inner tube od d	D-d
Semi-circular passage of diameter D	0,611D

5.2.2. Helically Coiled Pipes

Concerning helically coiled pipes, which are the most common heat exchangers in tanks, should be designed for every specific case according to different parameters of the tanks in order to ensure maximum efficiency. Those are usually still dimensioned for the prefabricated tanks in the market but for specific cases or new tanks designs some calculus must be done.

Figure bellow illustrates the helical coil. The pipe has an inner diameter 2r. The coil diameter is represented by 2RC (measured between the centres of the pipes). The distance between two adjacent turns is known as the pitch is H. The coil diameter is known as the pitch circle diameter (PCD). The ratio of pipe diameter to coil diameter (r/Rc) is the curvature ratio, δ. The ratio of pitch to developed length of one turn (H/2πRc) is termed the non-dimensional pitch, λ. Consider the projection of the coil on a plane passing through the axis of the coil. The angle, which projection of one turn of the coil makes with a plane perpendicular to the axis, is known as the helix angle, α. Consider

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any cross section of the pipe created by a plane passing through the coil axis. The side of pipe wall nearest to the coil axis is termed inner side of the coil and the farthest side is termed as outer side of the coil. Similar to Reynolds number for flow in pipes, the Dean number is used to characterise the flow in a helical pipe.

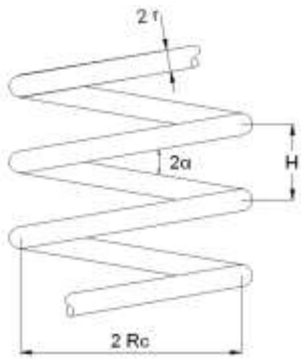

Figure: A Helical Pipe (Source: University of Ulster)

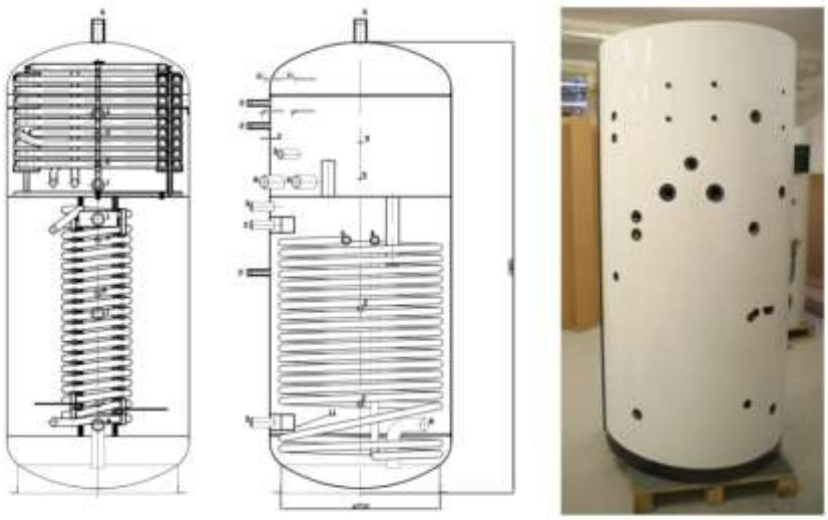

Figure: Helical pipe integration (Source: Regulus Tank)

The average Nusselt number is:

$$Nu_{av} = \frac{2r}{k}\left(\frac{q_m^{"}}{(T_{w,m} - T_b)}\right)$$

Where $T_{w,m}$ and $q_m^{"}$ are evaluated using the following expression:

$$\varphi_m = \frac{\int_0^{2\pi}(\varphi \Delta A)\, d\theta}{\int_0^{2\pi}(\Delta A)\, d\theta}$$

Where ϕ = k, Tw or q" as the case may be. Here ΔA is the area of elemental ring located along the wall to which the parameter is associated to. This is one example and a literature review has revealed a number of mostly experimentally derived calculations.

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For example, in calculating the Reynolds number, some equations assume a Reynolds number of >4000 i.e. turbulence. For low Reynolds numbers (<2000) where laminar flow regimes exist, alternative calculations may have to be used. However reducing the selected pipe diameters for example can increase the Reynolds number significantly (but at the expense of greater pumping costs and higher pressure drops). In the transition zone (2000 < Re < 4000), coefficients are difficult to predict and therefore this should be avoided, as moving between laminar and turbulent flow regimes and dramatically effect performance. Typically for water flowing in tubes, heat transfer coefficients of between 1000 and 5000 W/m²K are not uncommon while gases have much lower coefficients in the order of 10-300 W/m²K. Having determined the energy required and with knowledge of the temperature in the coil, the heat transfer surface may be determined using:

$$\dot{Q} = U\ A\ F\ \Delta Tm$$

Where U is the overall heat transfer coefficient, A is the Area, F is a correction factor for the ΔTm and ΔTm is the mean temperature difference between the coil and the bulk fluid i.e. water.

For coil-in-tank heat exchangers, the mean temperature difference is given by:

$$\Delta Tm = \frac{\Delta T_1 - \Delta T_2}{\ln \frac{\Delta T_1}{\Delta T_2}}$$

Where ΔT_1 and ΔT_2 are temperature differences between the fluids at each end of the heat exchanger.

The overall heat transfer coefficient U may be written as:

$$\frac{1}{U} = \frac{1}{h_{ex}} + \frac{d_{ex}}{2k} \ln \frac{d_{ex}}{d_{in}} + \frac{d_{ex}}{d_{in}} \cdot \frac{1}{h_{in}}$$

Where h is the heat transfer coefficient (W/(m²K)), d is the diameter of tube (m), k is the thermal conductivity of the tubes, and subscripts ex and in refer to external and internal aspects respectively.

The average internal convective heat transfer coefficient h_{in} of the helical coil can be evaluated using the heat transfer correlation for forced convection in helically coiled tubes obtained by Rogers et al., for the range $10^4 < Re < 6 \times 10^4$ where:

$$Nu_{in} = 0.023 Re^{0.85}\ Pr^{0.4} \left(\frac{d_{in}}{D}\right)^{0.1}$$

Where Re is the Reynolds Number, Pr is the Prandtl Number, D is the diameter of coil (m) and d_{in} is the internal diameter of the tube (m).

The h_{in}, Reynolds, Prandtl and Nusselt numbers are given by:

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$$h_{in} = \frac{Nu_{in}k}{d_{in}}$$

$$Pr = \frac{Cv}{k}$$

Where C is the fluid specific heat (j/kgK) and v is viscosity (Ns/m²).

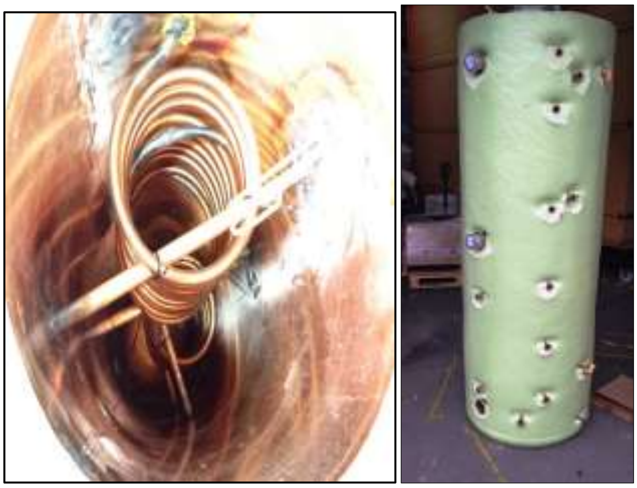

Figure: University of Ulster CST system (Source: University of Ulster)

Alternatively Fernández-Seara et al developed a numerical model in order to predict the heat transfer process and pressure drop in a vertical helical coil heat exchanger (HCHE) located inside a fluid storage tank in which water is used as inner and outer fluid. Natural convection was considered as boundary condition for the HCHE outer surface. Therefore:

$$U = \frac{1}{\frac{r_0 \, . \, ln\left(\frac{r_0}{r_m}\right)}{k} + \frac{1}{h_o} + \frac{1}{h_{fo}}}$$

Where h is the convection heat transfer coefficient (W/m²K).

5.3. PCM implementation

In *D2.1- Report on Storage Materials and Systems* an extensive compilation of Latent Heat Storage and PCM was made, all the information concerning applications, classification and main properties of PCM can be found on it.

5.3.1. *Storage System*

In order to integrate in Chess-Setup, PCM should be exchanging heat with water or another fluid through a heat exchanger or by direct contact as an active storage system.

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The heat and cool storage capacity of a water tank depends on the sensible storage capacity of water and the temperature difference within the water temperature curve. In case that PCM replaces (a part of) the tank water, the economic impact depends, among other things like on this water temperature difference. In the case of heat storage (50 to 90ºC) PCM will have a lower impact while in cool storage (10 to 15ºC) will have higher impact. PCM in a cool storage could reduce the storage volume considerably. In case of daily, weekly, monthly, or seasonal heat storage PCM reduces the water tank volume with only 10 to 15%, and possibly 25%, which is too small to have an economic impact.

On one hand, in case of temperature stratification in a vertical water tank the temperature at the bottom will be lower, and a solar collector water inlet at the bottom will improve the solar collector efficiency. PCM at the water tank bottom will extend the availability of this lower temperature. On the other hand, if temperature at the top will be higher, and a heat exchanger to heat potable water at the top will improve the operation time, PCM at the water tank top will extend the availability of a higher temperature.

In case that a (seasonal) storage temperature drops below the energy demand temperature, the temperature difference between both can be bridged by a heat pump. A water buffer between the heat pump and the energy demand can reduce and stabilize the required heat pump power, and a PCM buffer can stabilize the required heat pump temperature.

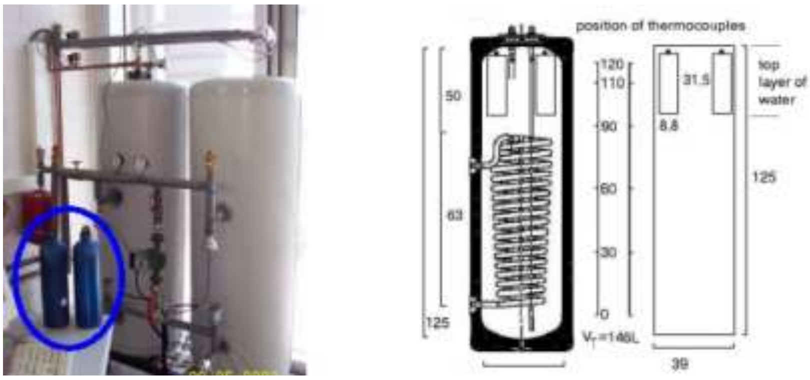

Figure: PCM modules included in domestic hot water tanks (Source: D2.1)

The PCM total cycle number (of phase changes) is an important value. To assess PCM for energy storage the production energy of PCM can be compared with the total energy which is stored by the total number of PCM phase changes during its lifetime. In case of seasonal heat storage, storing heat for the winter season, the number of phase changes is only one phase change per year. In that case, and at a lifetime of 50 years and a latent energy of 200 kJ/litre, the total energy which is stored is 10 MJ/litre of low exergy heat. Besides other (dominant) benefits and interests of seasonal heat storage, the production energy of PCM should be compared with this 10 MJ/litre and also the (higher) exergy value of the production energy of PCM should be considered.

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For zero emission solar energy storage, the total emission saved during the lifetime of the PCM system, should compete with, and exceed, the total emission caused by the production of the PCM system.

In case of waste heat transport PCM reduces the water tank volume, which also reduces the tank transport costs, and may have a positive effect on the economic impact. On the other hand, if PCM lifetime and that of its environment do not run parallel, or in case of unexpected PCM damage, the PCM system parts should be replaced or repaired.

The degree of PCM integration with its environment - PCM modules floating in a heat storage tank versus a PCM granulate mixed with a carrying construction for example - has an impact on the economical replacement or repair possibilities. In connection with the selection of the preferred energy storage system, the requirements can be described more in detail such as recyclability for example.

In case that a stable storage temperature is an advantage for a heat pump, PCM could also add advantage by reducing the energy system as a whole, and, besides the storage volume, reduce the heat pump power, and, if electric, the power peak in the electric grid.

A heat pump powered system, applied for domestic use for example, requires 25 kW power per house for only the potable water (shower) heating, while the indoor climate heating only requires 5 kW power or even less.

A PCM buffer for shower water heating could reduce this required 25 kW power in case that the PCM buffer can supply this power itself, and in that case the PCM buffer will also be co-financed by the reduced heat pump power and its investment.

Due to the low conductivity of PCM, the required power is an important condition for the storage system design, and to improve the PCM heat exchange the following PCM module, composite and mixture can be considered:

- Improving the heat exchange surface by macro-encapsulated cassettes in water.
- Improving the conductivity by additives such as graphite-paraffin composites.
- Improving the heat exchange capacity by PCM slurry circulation in heat exchanger.

5.3.2. Properties of Materials

PCM is characterised by its phase changing temperature - such as shown in the table below - and its energy content (and heat conductivity), while the storage system design will characterize its energy density and power by the choice between, and the selection of, PCM macro-, micro- or molecular-encapsulations, PCM composites, and PCM slurries.

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The phase changing temperature (T) and energy content or enthalpy change (E) of organic and inorganic phase changing materials, compared to water, are:

PCM	T ˚C	E	
		kJ/l	kJ/kg
Salt water	-80 to 0	200 to 300	
Water	0		333,55
Gas hydrate (clathrate hydrate)	0 to 30	200 to 300	
Water	100		2257
Paraffin	-30 to 130	100 to 200	
Salt hydrate	5 to 130	200 to 450	
Salt hydrate (eutectic mixture)	>130	200 to 450	
Sugar alcohol (development)	90 to 180	150 to 500	

The IEA Implementation Agreement 'Energy Conservation through Energy Storage' (ECES) Annex 25 'Surplus Heat Management using Advanced TES for CO2 mitigation' Final Report (2015) summarizes the today available PCMs and its melting enthalpy (kJ/kg) and melting temperature (˚C):

PCM	T (˚C)	kJ/kg
Copper foam	n.a.	n.a.
PCM-A	42-44	135
PCM-B	43	137
PCM-C	35	120
PCM-D	32	102
$NaNO_3$	308	162.5
$NaCl$-$MgCl_2$ eutectic	444	292
$MgCl_2$	714	454
E-21	-	-
Climsel C-18	-18	306
E-21	-21	n.a.
Gypsum impregnated with 26.2%wt RT21	18 to 23	34
d-mannitol	162 to 170	246
Hydroquinone	168 to 173	206
RT27 macroencapsulated	28	179
SP25 macroencapsulated	26	180
S46 in HDPE flat plates	46	n.a.
S10 in HDPE flat plates	10	n.a.
EPDM + EAFD + RT21 + Zn stearate	22	18
Microencapsulated capric acid	23 to 27	70 to 100

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Microensapsulated lauric acid	23 to 27	70 to 100
Microensapsulated myristic acid	23 to 27	70 to 100
Caprylic acid microencapsulation with urea-formaldehyde	0 to 20	94 to 106

5.3.3. Costs

The selection of the material to be used in latent heat storage is not easy. Availability and cost are usually the main drawbacks for the selection of a technically suitable material.

Commercial paraffin waxes are cheap with moderate thermal storage densities (~200 kJ/kg or 150 MJ/m3) and a wide range of melting temperatures. They undergo negligible sub cooling and are chemically inert and stable with no phase segregation. However, they have low thermal conductivity (~0,2 W/m˚C), which limits their applications.

The main limitation of salt hydrates is their chemical instability when they are heated, as at elevated temperatures they degrade, losing some water content every heating cycle. Furthermore, some salts are chemically aggressive towards structural materials and they have low heat conductivity. Finally, salt hydrates have a relatively high degree of super cooling.

Hydrated salts are attractive materials for use in thermal energy storage due to their high volumetric storage density (~350 MJ/m3), relatively high thermal conductivity (~0,5 W/m˚C), and moderate costs compared to paraffin waxes, with few exceptions.

The price of commercial PCMs is typically in the range from 0.5 €/kg to 10 €/kg, which has a large influence on the economics of PCM applications. The price of salt hydrates is usually low, in the order of 1 to 3 €/kg unless bought in pure form.

For a rough estimate an energy price of 0,05 €/kWh for heat can be assumed. This means that 3.600 kJ cost 0,05 €. Taking an average storage density of a PCM of 180 kJ/kg, 20 kg of PCM are necessary to store 3.600 kJ (=1 kWh), an amount of heat that has a value of 0,05 €.

20 kg of PCM however cost at least 20 kg*0,5 €/kg = 10 €. To store heat with a value that equalizes the cost of the necessary investment for the PCM, a number of 10 € / 0,05 € = 200 storage cycles are necessary.

Additional investment cost for the storage container and heat exchanger, as well as the stored heat which is also never completely free, have not even been taken into account. Seasonal storage using PCM is therefore far from being economic at current prices for fossil fuels. To be competitive in energy systems, one should try to charge and discharge storage daily, or even in shorter periods. There are however exceptions. For example if an application has no connection to the energy grid, e.g. in the cargo bay of an airplane, the common energy price is not applicable and the economic situation can be much better.

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5.3.4. Real Cases

PCM energy storage systems can be divided into active and passive systems. Active systems are intermediate storages, using a transfer medium actively moving the heat or cold to the storages. Passive systems are building materials or building components in which PCM is integrated, to increase the thermal mass of the building for example. The CHESS-SETUP projects will use buffer and storage tanks, so the following cases of today and of the past are related to active systems only.

LaTherm based in Dortmund developed a 20 feet container for waste heat transport between industry and buildings. The natrium acetate PCM container has a 2,5 MWh heat capacity, 3 to 6 hours loading time, and 0,1%/day heat loss.

Figure: KTG Energie / LaTherm

PowerTank based in Sonneberg developed a heat transport system in a 20 feet container with 138 BHKW Zellen (200 x 1800 mm cylinders), including 60 °C PCM, containing 600 kWh at 20 K temperature difference.

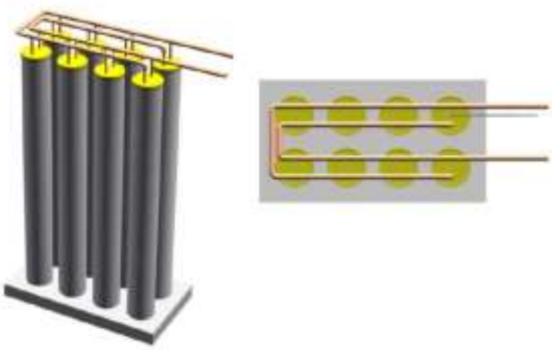

Figure: PowerTank, Assembly latent cells

Alfred Schneider based in Lahr developed a Latentwärmespeicher (LWS) which contains natrium acetate PCM with a heat capacity of 122 kWh/m3 and 58,5 °C exchange temperature.

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Figure: Latentwärmespeicher LWS

PCM Products of EPS based Yaxley Petersborough developed PCM encapsulations BallICE, which are balls with 40 mm diameter, and TubeICE, which are bottles or tubes with 50.00 mm diameter and 1 m height.

Figure: EPS, PCM Products, BallICE

Haase GFK-Technik based in Grossröhrsdorf developed Das Eisspeichersystem as part of a heat pump and solar collector system, using water as a PCM instead of paraffin or salt hydrate.

Source: Haase GFK-Technik, Das Eisspeichersystem

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6. Investment Costs

As every system is unique and depends of many circumstances it is very difficult to establish or predict a specific cost or ratio for each technology. Each system's cost may vary significantly according to its constraining factors (location, new/existing construction, access availability, materials disposition, etc.).

In any case, pilots that have already been constructed may offer good reference values in order to have an average ratio. Regarding the different projects developed in Germany (information provided by Solites) the following graphics have been done in order to see the cost trends and differences for each individual type of thermal energy store:

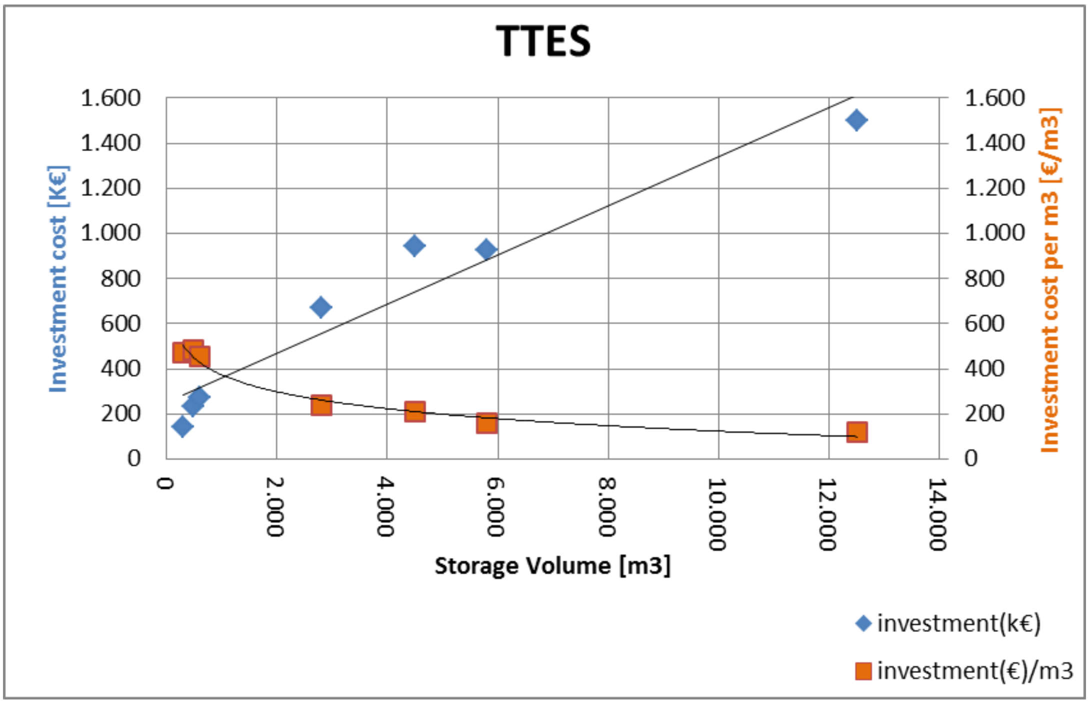

Figure: TTES Investment cost and investment/m³ evolution regarding the different projects developed in Germany (Source: Solites, own elaboration)

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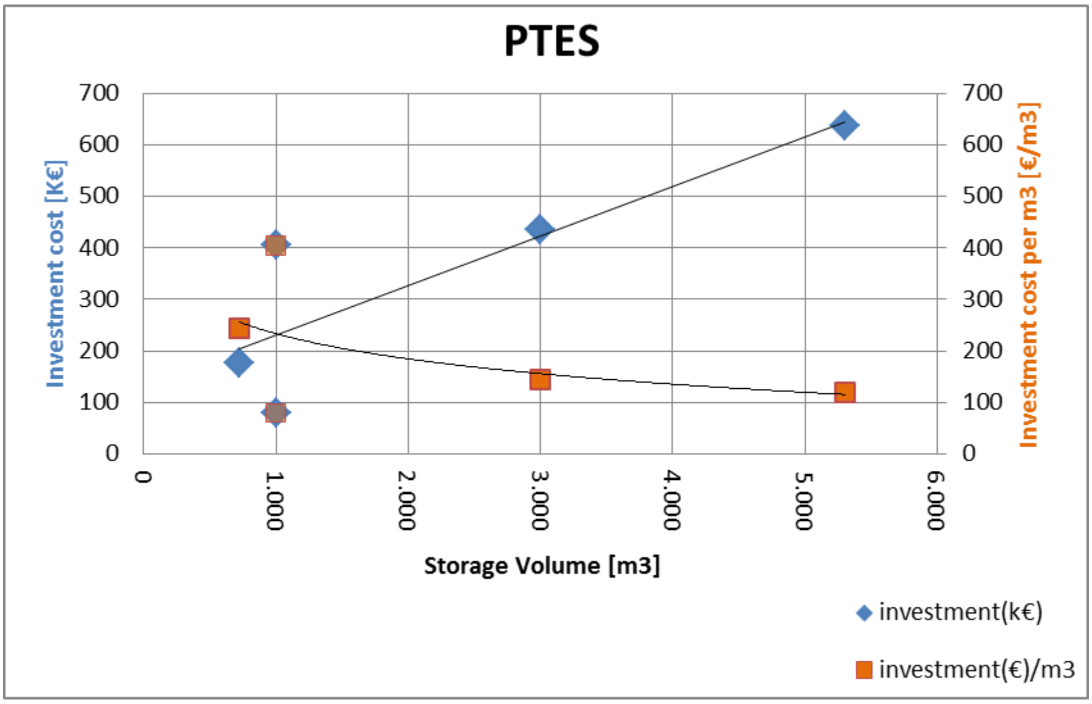

Figure: PTES Investment cost and investment/m³ evolution regarding the different projects developed in Germany (Source: Solites, own elaboration)

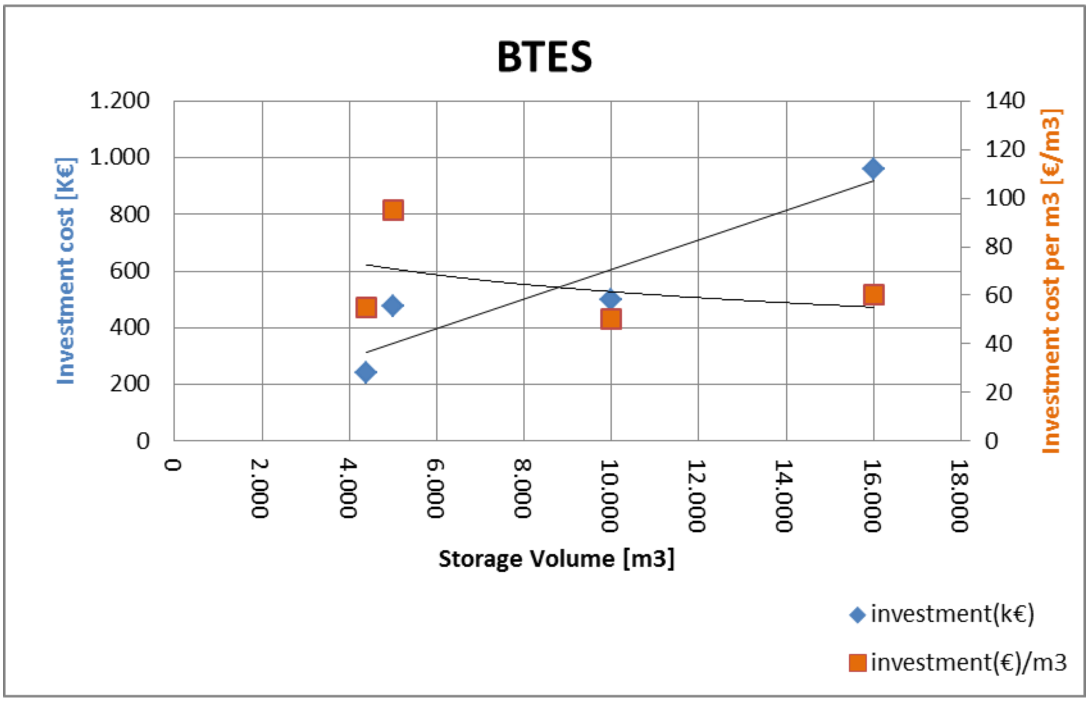

Figure: BTES Investment cost and investment/m³ evolution regarding the different projects developed in Germany (Source: Solites, own elaboration)

For the ATES, the only example found is the Rostock-Brinckmanshöhe with a 5.000m³ storage volume with an investment cost of 200k €, which means an average of 4 €/m³.

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In order to see the viability and the cost saving potential of the project the investment cost should be compared with the heating production costs with the conventional systems, calculating the future demand, the boiler efficiency and the costs of the fuel. With this information the savings could be obtained in order to see the return period on the investment.

7. CHESS SETUP pilot's analysis

Once described all the technologies a quick review of the possible implementation in the CHESS SETUP pilots is done.

7.1. Sant Cugat

The Sports Centre of Sant Cugat is located in the middle of the city centre surrounded by buildings and a parking as well as all the urban services underground. This restricts the use technologies such as the geothermal alternatives and the big TTES and PTES on the ground. The storage solution should be found inside the building.

Figure: Aerial photo of Sant Cugat Sports Centre

Some available spaces are listed below:

- PAV 2 Access / Parking
  - Available space: 910m^3
  - Good accessibility
  - Far from the heating production room

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Figure: PAV 2 Access/Parking space

- Water Pump Room
    - Available space: 199 m^3
    - Difficult accessibility
    - Need of possible reorganization of the existing equipment
    - Close to the heating production room

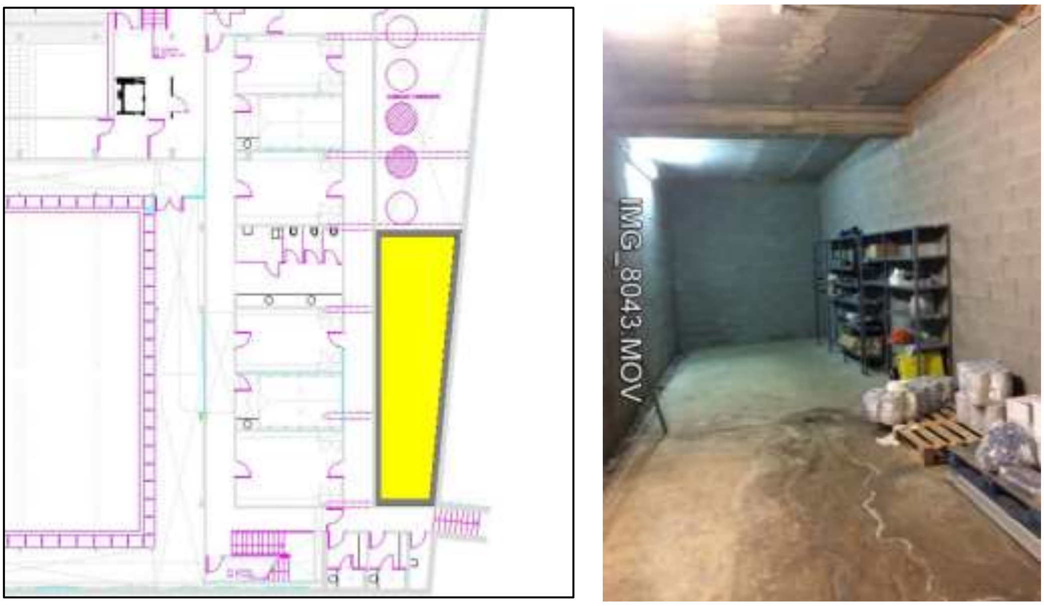

Figure: Water pump room space

- Sports Hall 2
    - Available space: 2.300 m^3
    - Difficult accessibility
    - Big and expensive structural interventions

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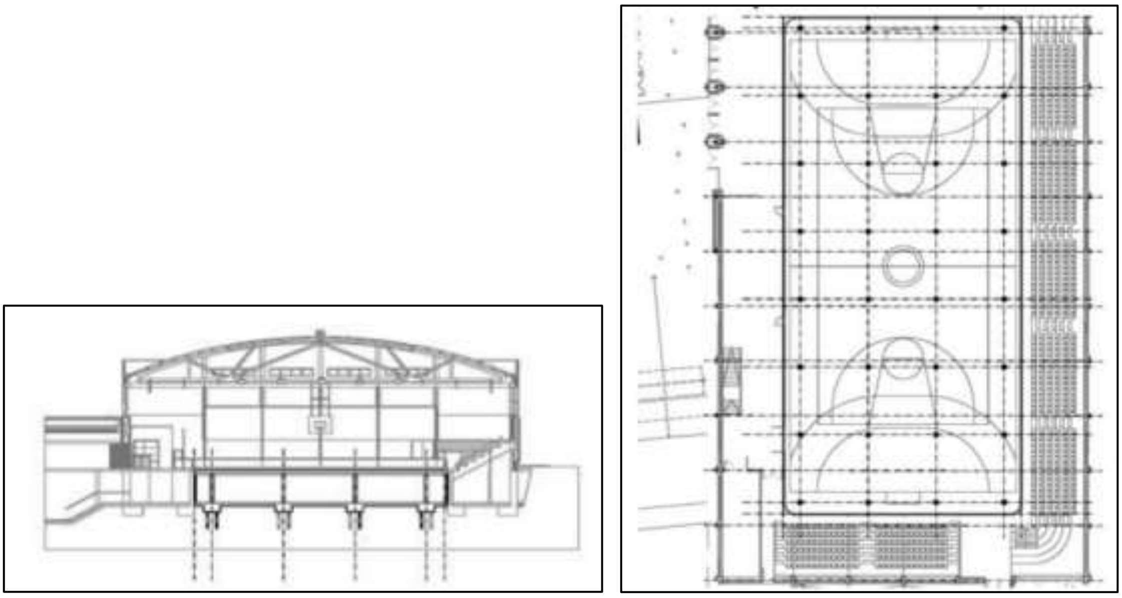

Figure: Sports Hall 2 space

- Corridor
  - Available space: 250 m^3
  - Good accessibility
  - Close to the heating production room

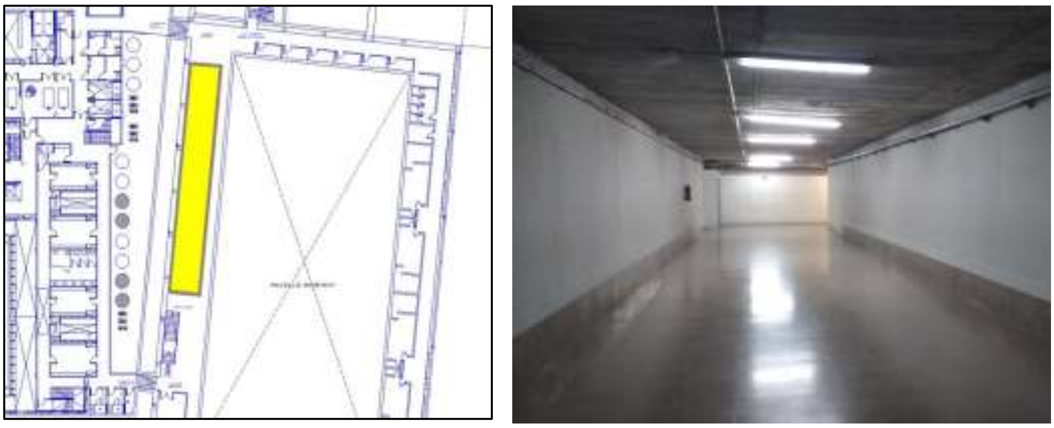

Figure: Corridor space

In all the cases the favourable external temperature would benefit the insulation thickness.

Concerning the energy source, solar thermal or PVT panels seems to be the best alternative given the availability of surface in the decks of the pavilions. In any case, a reinforcement of the structure will be probably needed for the installation of the panels.

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Figure: Sport center roof spaces

The number of panels should be chosen according to the whole system characteristics. Due to its orientation to the south the best place to install the panels would be PAV3.

Concerning the construction impacts, the main installation constrain is the accessibility to the final tank location, this will play an essential role in the chosen tank solution.

About the construction works, a special caution in risk preventions, in order to avoid personal injuries, will be necessary as the sport centre users will be carrying out their activities during the construction of the pilot. It will also be important to control the noise and waste produced in order to minimise them and reduce the affections.

Finally, concerning the works and maintenance of the panels, all the measures needed to ensure the security of the personnel that will work in heights must be installed.

7.2. Lavola

As Sant Cugat's pilot, the eco-building of Lavola is located in an urban area. However it is also surrounded by many areas without constructions.

If these surrounding areas were available for the project a tank dug into the ground would be a good alternative, as well as BTES or ATES system if the conditions of the soil are suitable to do so. In that case, the accessibility and the working space will make the works much easier. Concerning the environmental impacts all the measures to avoid the contamination of the soil must be considered as well as reduce the noise and the dust produced. A part from Lavola's building there is a school in the building on the left so the security rules must be intensified.

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Figure: Building of Lavola

Figure: Aerial photo of the building

On the other hand, if the terrains were not available due to property reasons or urban plans, it is necessary to find solutions inside the building. Regarding the different available spaces these could be:

- The existing rain-water-harvesting tank, with a capacity of 3.8m^3. Despite the low capacity of the tank, the investment cost would be reduced.

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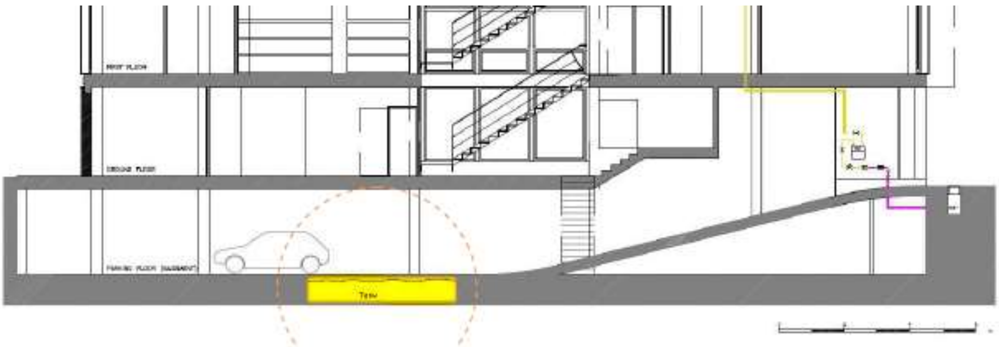

Figure: Location of the existing rain-water harvesting tank

- Part of the parking zone, with 4m^3 of available space. Considering the dimensions and the parking accessibility, a prefabricated tank would be a good option.

Like in Sant Cugat, the favourable external temperature would benefit the insulation thickness.

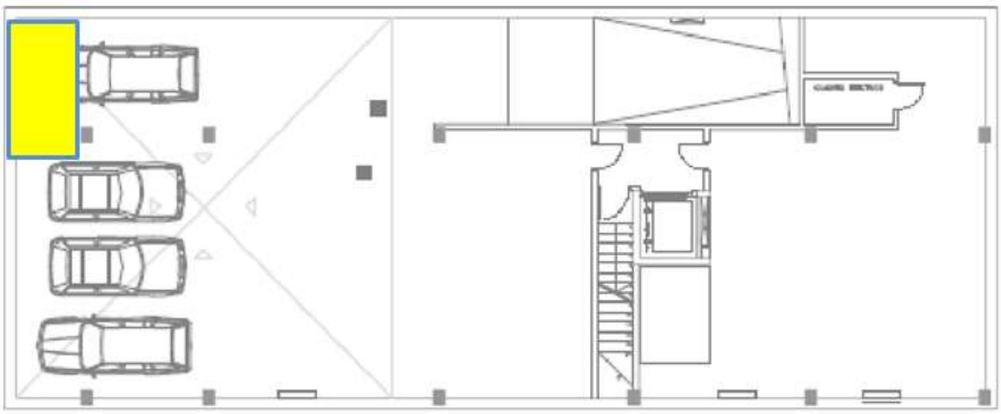

Figure: Parking available space

- Installation of a tank in the roof of the building. In that case a structural study must be carried out in case reinforcement is needed. It would require a bigger thickness.

Concerning the energy source, there is space in the roof where solar panels could be installed. For the panels installation all the measures and instruments needed to ensure the security of the personnel that will work in heights must be considered.

7.3. Corby

The advantage of the Corby pilot is that it is the only one that is integrated in a new construction and the solution can be designed from the beginning in the project.

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Despite Corby's solution is already designed for this particular project (geothermal solution) the other alternatives could be also implemented and the investment cost would be much lower than introduce the technology in the existing buildings.

For new urban development plans, the centralisation of the production is a good alternative concerning investment, operation and maintenance.

Figure: Aerial Photograph and overall Plan of the Corby Pilot location.

8. Guidance on Maintenance and Operation Costs

System maintenance is a very important part to take into account since the first minute of service. In this point the objectives and the different type of maintenance that should be applied are summarised and a plan of maintenance for the different Chess-Setup system components is made.

8.1. General maintenance objectives

The major objectives of the maintenance plans for the Chess-Setup systems are as follow:

- To keep the perfect working and preservation state of the installation and equipment.
- Guarantee the permanent performance availability, equipment functions and elements to preserve.
- Ensure the continuous operation, effectiveness and efficiency, and guarantee that the eventual stops will be the minimum and the technically essentials.

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- Achieve a high feasibility and security degree, preventing failures that can affect the normal development of the activities of the centre.
- Have an integrated action plan that ensures a correct operation, conduct and maintenance. This will allow following an energy saving plan with the adequate energy management.
- Keep the computerised management updated.
- Keep the documentary archives, schemas, plans, project memories and all the technical documentation of the installations associated to the service updated.

8.2. Types of Maintenance

Different types of maintenance must be applied in order to accomplish the objectives described. Those are numbered and explained as follows:

8.2.1. Preventive Maintenance

The preventive maintenance comprises all the systematic actuations needed to maintain the Chess-Setup system, the installation and the equipment optimal working conditions in order to prolong their lifespan and maintain their performance similar to the project performance.

As all the elements to maintain are clear and the preventive maintenance actuations are characterised by their periodicity, it is possible to systematise the process in order to identify previously the needs in term of hours, personnel and materials and programme all the preventive actuations to do.

The maintenance company should elaborate a Preventive Maintenance Planning that encompasses all the installations and equipment and with the following characteristics:

- An annual preventive maintenance operations planning will be done for all the equipment required.
- The specific tasks to carry out for each installation should be detailed, with the expected execution time, the type of personnel assigned and the frequency.
- Preventive maintenance routines will be implemented and all the operations done will be registered, with the real time spent, the number and type of detected incidences and the solution taken in each case.
- The Preventive Maintenance Plan should be elaborated with a chart of actions that will include the necessary cycles to guarantee the functionality and preservation of the installations, civil works and others. These cycles will have the convenient recurrence, according to the installation possible needs, with a minimum cost criteria. The maintenance sheets should have:
    - Name of the system
    - Specific element of the system
    - Description of the actions to be carried out and materials needed

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  - Frequency of the action
- The preventive maintenance chart will also distribute the planned actions during the 52 weeks of the year. To make a correct plan of the preventive maintenance operations is recommended that the control of the cycles and the realisation of the activities are made with informatics support, such as a Computerized Maintenance Management System (CMMS).

8.2.2. Legislative Maintenance

Legislative Maintenance will not technically differ from Preventive Maintenance and will be carried out following predetermined cycles with a planning fixed by the different official organisms. The difference is that in the Preventive Maintenance the operations are fixed according to the professional experience and the suppliers recommendations whereas the Legislative Maintenance should be rigorously applied according to current legislations.

There are two types of technical reviews in the legislative maintenance:

- The obligatory inspections carried out by administration collaborating companies.
- The obligatory reviews carried out by the maintenance company.

The elements that require legislative maintenance usually are:

- Low voltage installation
- Chillers and heat pumps
- Protection and detection systems and fire alarms
- Boilers, boiler burners and fireplaces
- Pressure equipment
- Gas distribution systems and networks
- Other fuels distribution systems and networks, liquids or gases
- Grounding networks
- Water networks, DHW, DCW, heating and cooling
- Water distribution systems affected by Legionella Legislation
- Others that can be affected by current legislation

The maintenance company must have all the information and official books updated with the last legislative review so that can be checked by the Official Organisms, insurance companies, etc. The responsible of maintenance of the installation will keep all of this information.

8.2.3. Control Maintenance

The Control Maintenance includes all those operations of checking, verification, operation and adjustment, necessaries for the installations to offer at all times the

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service provision without interruptions or incidents. This includes the commissioning and stops of the installations, according to the previous established criteria, the surveillance and the routes of inspection and function check.

As an essential part of the building control tasks, the maintenance company should execute all the actions needed in order to reduce the energy consumption (water, gas and electricity) according to a rational use, comfort and minimum cost.

The control routes are considered in this type of maintenance. The daily installation route is focused in ensure the continuity and good performance of the equipment and installations considered as critical.

The proposed route should be defined according to the operating conditions:

- The route will be based on the control points monitoring (installations and equipment) according to their proximity.
- Annotation of the total and partial water, gas and electricity meter readings. Computerized control of the data and analyse of deviations.
- Annotation of the working parameters of the equipment (system balancing, emergency batteries, transformers, chiller, etc.)

With the data obtained during the route the following actions will be done:

- Computerized analyse of the installation consumption tendencies. From the energy consumption of the different subsystem registered the evolution of the consumption will be analysed in accordance with the climatology (temperature and humidity), seasonality (summer, winter), activity in the centre, etc.
- Take actions to reduce the energy consumption to a minimum in water, gas and electricity installations, following rational use, comfort and minimum cost criteria and optimal tariffs selection. Once there will be enough knowledge of the installations, certain elements with a high consumption could be, in a controlled way, stopped in order to offer additional energy savings without affecting the system activity.

8.2.4. Corrective Maintenance

Corrective Maintenance is all of the non-systematic technical works which objective is to solve the malfunctions and deficiencies that might occur in the system or equipment.

Depending on the gravity there will be a different degree of response in order that the solution arrives more or less rapidly. The breakdowns are usually classified as follow:

- Urgent resolution
    - Those breakdowns that may represent a danger to public or serious installation damage require an immediate response. Also the ones that force to stop the activity or suppose a serious inconvenient for its development.

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  - In order to cover this type of breakdowns at any time a good solution is to dispose of a 24h assistance service.
- Non-urgent resolution
  - All the breakdowns not identified as urgent. They can be solved during a programmed maintenance visit.
  -

8.3. Chess-Setup maintenance plans

In the following chapters the different maintenance plans for the main Chess-Setup elements are developed, taking into account all the types of maintenance previously described. In the tables the different actions are described with the frequency that must be carried out.

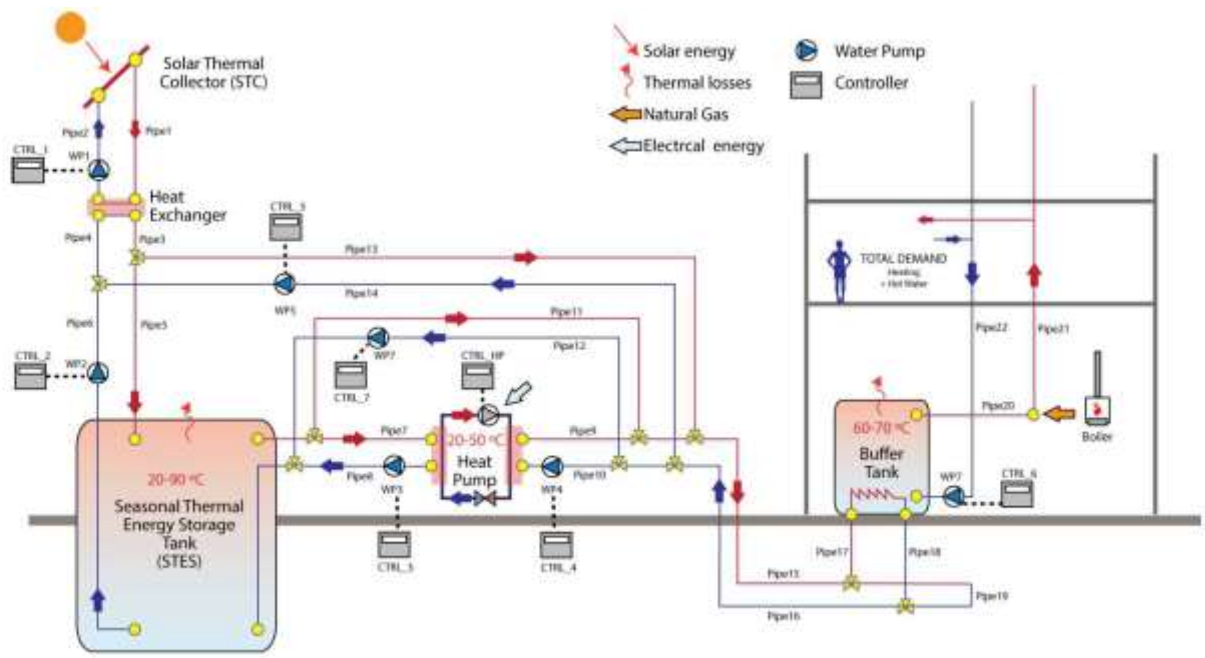

Figure: Chess-Setup reference case (Source:D3.3)

8.3.1. STES Maintenance

VERIFICATIONS AND OPERATIONS OF MAINTENANCE	W	BW	M	BM	Q	SM	A
Verify the anomalies of the security elements			✓				
Review of the automatic associated control system					✓		
Verify the watertightness of the system (tank, valves, joints, etc.)	✓						
Verify the effective functioning of the level sensors system			✓				
Check the state of the joints and valves of the tank					✓		
Check the connections of the tank to the piping system					✓		

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	W	BW	M	BM	Q	SM	A
Check the absence of obstructions in the emptying taps of the tank					✓		
Check the functioning of the entrance and exit meter					✓		
Verify the watertightness of the interception valves						✓	
Review the state of the thermal insulation material							✓
Verify the water treatment system (water input)			✓				

W:Weekly, BW:Biweekly, M:Monthly, BM:Bimonthly, Q:Quarterly, SM:Six-monthly, A:Annual

8.3.2. Heat Pump Maintenance

	W	BW	M	BM	Q	SM	A
VERIFICATIONS AND OPERATIONS OF MAINTENANCE							
Verify leaks of refrigerant			✓				
Check the refrigerant gas loads (bubbles in the viewer)			✓				
Verify the lack of humidity in the refrigerant (humidity in the viewer)					✓		
Verify the overheating of the thermal expansion valve			✓				
Check the oil condition. Replace if necessary.			✓				
Review the oil load in all he compressors. Add if necessary.			✓				
Review the functioning of the crankcase resistance					✓		
Verify earthing					✓		
Verify the control of the compressors capacity					✓		
Readjust the electrical connections of each compressor					✓		
Change compressors sequence					✓		
Check strange noises of the compressors			✓				
Check contactors: movement and contacts			✓				
Check circuit breakers (readjust connections)			✓				
Check and adjust the flow valve					✓		
Water control thermostat regulation					✓		
Write down the oil pressure switch cut-off value					✓		
Bearing greasing							✓
Pressure switch and thermostat contrast and adjustment			✓				
Review and clean of the water filter							✓
Write down the anomalies codes			✓				
Check corrosion							✓
CLEANING							
Condenser mechanics cleaning							✓
MEASUREMENT							
Water circuit manometer lecture			✓				
Evaporator's thermal jump			✓				
Condenser's thermal jump			✓				
High and low pressure of the refrigerating circuits			✓				
Compressor's suction and discharge pressure			✓				

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	W	BW	M	BM	Q	SM	A
Liquid's line temperature			✓				
Refrigerating circuit suction aspiration temperature			✓				
Refrigerating circuit overheating level			✓				
Refrigerating circuit subcooling level			✓				
Oil temperature			✓				
Compressor and crankcase's resistances consumption			✓				

W:Weekly, BW:Biweekly, M:Monthly, BM:Bimonthly, Q:Quarterly, SM:Six-monthly, A:Annual

8.3.3. Buffer Maintenance

	W	BW	M	BM	Q	SM	A
VERIFICATIONS AND OPERATIONS OF MAINTENANCE							
Visual inspection of leaks			✓				
Visual check of the piping system. Look for leaks.			✓				
Review of the galvanic anode and change if necessary						✓	
CLEANING							
General clean of the water filters			✓				
Heating elements and tank cleaning							✓
General review of the tank isolation							✓
Verify the security devices							✓
MEASUREMENT							
Hot water temperature distribution			✓				
Hot water consumption			✓				

W:Weekly, BW:Biweekly, M:Monthly, BM:Bimonthly, Q:Quarterly, SM:Six-monthly, A:Annual

8.3.4. Solar Installation Maintenance

	W	BW	M	BM	Q	SM	A
VERIFICATIONS AND OPERATIONS OF MAINTENANCE							
Verify the circuit's temperature			✓				
Review the level of glycol			✓				
Verify the leakproofness of the circuit			✓				
Verify the absence of condensation during the central hours of the day					✓		
Verify cracks, deformations corrosions or joint leaks					✓		
Verify the lack of degradation and corrosion in the absorption tube					✓		
Manual purge of the primary circuit					✓		
Verify the state of the piping system and isolation of the circuit						✓	
CLEANING							

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	W	BW	M	BM	Q	SM	A
Cleaning of the panel glasses with water and suitable product			✓				

W:Weekly, BW:Biweekly, M:Monthly, BM:Bimonthly, Q:Quarterly, SM:Six-monthly, A:Annual

8.3.5. Other Equipment

PUMPS

	W	BW	M	BM	Q	SM	A
VERIFICATIONS AND OPERATIONS OF MAINTENANCE							
Test the backup pump, in the case of double pumps			✓				
Inspection of operation: noise and vibrations			✓				
Check the wear of the bearings			✓				
Verify the lubrication and greasing of the bearings			✓				
Verify the lack of leaks in the joints			✓				
Verify the drain of refrigeration and absence of leaks (check obstructions)			✓				
Verify the impulse pressure			✓				
Verify the non-return valves			✓				
Verify the cut-off valves						✓	
Check the electric connection terminals							✓
Check anti-vibration sleeves							✓
Leakproofness and pipe connections inspection							✓
Verification of the circuit breaker							✓
Vibrations and fixations check							✓
Verification and adjustment alignment of the group							✓
Verification and adjustment of the earthing							✓
Manometers and thermometers contrast							✓
CLEANING							
Aspiration filters			✓				
MEASUREMENT							
Work pressure			✓				

W:Weekly, BW:Biweekly, M:Monthly, BM:Bimonthly, Q:Quarterly, SM:Six-monthly, A:Annual

PLATE EXCHANGER

	W	BW	M	BM	Q	SM	A
VERIFICATIONS AND OPERATIONS OF MAINTENANCE							
Verify the absence of leaks			✓				
Check joints							✓
Thermal insulation review							✓
Verify the lack of corrosion							✓
Check the heat exchange (clean when necessary)							✓

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	W	BW	M	BM	Q	SM	A
CLEANING							
Primary and secondary circuit							✓
MEASUREMENT							
Primary circuit entrance and exit temperatures			✓				
Secondary circuit entrance and exit circuit temperatures			✓				

W:Weekly, BW:Biweekly, M:Monthly, BM:Bimonthly, Q:Quarterly, SM:Six-monthly, A:Annual

PROBES

	W	BW	M	BM	Q	SM	A
VERIFICATIONS AND OPERATIONS OF MAINTENANCE							
Operational control					✓		
Verify the signalling alarm					✓		

W:Weekly, BW:Biweekly, M:Monthly, BM:Bimonthly, Q:Quarterly, SM:Six-monthly, A:Annual

PIPE SYSTEM

	W	BW	M	BM	Q	SM	A
VERIFICATIONS AND OPERATIONS OF MAINTENANCE							
Position and state of the pipe supports							✓
Review of the thermal insulation							✓
Verify the lack of corrosion							✓
Verify the lack of expansion							✓

W:Weekly, BW:Biweekly, M:Monthly, BM:Bimonthly, Q:Quarterly, SM:Six-monthly, A:Annual

VALVES

	W	BW	M	BM	Q	SM	A
VERIFICATIONS AND OPERATIONS OF MAINTENANCE							
Verify and adjust the closing devices							✓
Verify the leaks in the stuffing box							✓

W:Weekly, BW:Biweekly, M:Monthly, BM:Bimonthly, Q:Quarterly, SM:Six-monthly, A:Annual

ELECTRIC PANEL

	W	BW	M	BM	Q	SM	A
VERIFICATIONS AND OPERATIONS OF MAINTENANCE							
Verify the state of the fuses			✓				
Check the regulation of the circuit breakers			✓				
Verify circuit breakers and differentials			✓				

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Check overheated cables			✓				
Verify and readjust electrical connections			✓				
Verify switches and circuit breaker function			✓				
Contrast and adjustment of measuring devices			✓				
Review the protection devices function			✓				
Verify the earthing			✓				
Verify the electrical insulation			✓				
CLEANING							
Electric panel			✓				
MEASUREMENT							
Operating hours			✓				
Electrical consumption of the refrigerant system			✓				

W:Weekly, BW:Biweekly, M:Monthly, BM:Bimonthly, Q:Quarterly, SM:Six-monthly, A:Annual

8.4. Maintenance Service

Finally, in order to follow up and ensure the effectiveness of the maintenance planning for the different Chess-Setup systems the following system support service and recommendations are done:

- Use the necessary functions for a correct organisation, coordination and tracking of the human, technical and material resources related with the maintenance in order to obtain the maximum optimisation according to the planned needs.
- Have a technical advice for the initial technical and evaluation reports, as well as studies and basic projects and budgets for the adaptation of the installations required.
- The use and deliverance of annual certifications with the controls and measurements of the legislative operations concerning the different elements of the system as well as the maintenance book update.
- Deliverance of the reports set out in the different maintenance plans proposed, specially the technical ones.
- Improve the inventory management and its constant update.
- Process all the documentation of guarantees, technical datasheets, etc. of certain materials and elements.
- Meet the particular needs of climate and energy saving improvement of the systems after their construction and firsts periods of function, proposing technical improvements in the materials and elements and management of the services.

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9. Conclusions

Tank Thermal Energy Storage (TTES) and Pit Thermal Energy Storage (PTES) are good alternatives to develop, the shape and dimensions of these storage tanks are very varied and depend on each project requirement, space availability and construction technique. Whereas TTES have the widest range of utilization possibilities, PTES are dug into the ground but close to the surface in order to reduce excavation costs.

In this type of STES thermal insulation layers take a substantial part within the costs investments and costs savings, this is why one of the principle design decisions is in the tank's layers to avoid storage heat losses. Thermal insulation materials in building constructions can be applied for seasonal storage systems in case that the insulation material has a relatively high thermal conductivity and temperature resistance. In this term the market offers a high variety of materials with different costs and characteristics (thermal conductivity, density, thickness, etc.). Meanwhile, water vessels for energy storage may also require water barriers in case that the vessel construction or thermal insulation is not water proof, or contains open seams, then a membrane layer should be installed.

Concerning building integration, besides the size of the indoor space, especially the accessibility to the building site and this indoor space could limit the storage volume. Modular tanks and monolith tanks are basically the most distinguished and are ideal for existing building where spaces may be at a premium because of their very flexible in design. There is a huge variety in the market and can be constructed with various materials like concrete, metal, plastic or wood.

For Borehole Thermal Energy Storage (BTES) and Aquifer Thermal Energy storage (ATES) soil properties play an essential role as the efficiency of the thermal energy storage systems is highly influenced by many parameters such as the thermal conductivity, thermal capacity, energy density or diffusivity of the soil.

Looking at system's configuration those can be closed and open: Closed systems, which are the most used for BTES, allow taking profit of the external levels of the surface when the permeability of the soil does not permit to obtain heat from the groundwater, they can be horizontal (easiest ones to install but with space limitation) or vertical. On the other hand, open systems used for ATES are a good choice for places with alluvial groundwater presence as they are simple, cheap and offer a good performance.

Concerning the internal structure of the tank, stratification devices, heat exchangers and Phase Change Materials (PCM) implementation are good alternatives in order to maintain optimal conditions and lead longer operation.

For stratification and heat exchangers devices there are many different concepts for internal structure devices in the market in order to heat and maintain the temperature of the tanks. Almost all of them are designed for small storage systems and there is not much experience available for large scale applications. There are many factors

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influencing the efficiency of a thermal storage system such as height, insulation, shape, flow rates, thermal bridges, etc., for this reason many studies and simulations should be done for every specific case in order to design the optimal internal system and heat transfer into the tank.

The use of PCM in the upper parts of the tank could reduce the storage volume considerably, this reduces the tank transport costs and may have a positive effect on the economic impact taking into account that PCM installation would increase storage cost. The selection of the material to be used in latent heat storage is not easy, availability and cost are usually the main drawbacks for the selection of a technically suitable material but PCM selection should finally be adapted to charging and discharging temperatures.

Finally, in order to keep the perfect working and preservation state of the installation and equipment, a maintenance plan should be established for the different elements of the system. This plan must take into account the obligatory legislative actuations established, the recommendations from the suppliers, corrective interventions and many other actuations of control and prevention. This will guarantee the permanent performance availability, equipment functions, elements preservation and will ensure the continuous operation, effectiveness and efficiency of the installation.

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10. Acronyms

APP: Atactic Polypropylene

ATES: Aquifer Thermal Energy Storage

BTES: Borehole Thermal Energy Storage

CG: Cellular Glass

CHP: Combined Heat and Power

COP: Coefficient of Performance

CR: Polychloroprene or Chloroprene Rubber

DHW: Domestic Hot Water

ECB: Copolymer Bitumen

EPDM: Ethylene propylene diene monomer

EPS: Expanded Polystyrene

HDPE: high-density polyethylene

LCA: Life Cycle Analysis

LDPE: Low-Density Polyethylene

LHS: Latent Heat Storage

PCM: Phase-Change Material

PC: Polycarbonate

PE: Polyethylene

PES: Polyester

PIR: Polyisocyanurate

PMMA: Polymethyl Metacrylate

PF: Phenolic Foam

PP: Polypropylene

PU: Polyurethane

PTES: Pit Thermal Energy Storage

PVC: Polyvinyl Chloride (PVC)

SHS: Sensible Heat Storage

SSHS: Seasonal Sensible Heat Storage

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STES: Seasonal Thermal Energy Storage

TES: Thermal Energy Storage

TTES: Tank Thermal Energy Storage

UF: Urea Formaldehyde

VCI: Variable Conductance Insulation

VIP: Vacuum Insulated Panel

VSI: Vacuum super insulation

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A1. Appendix 1: Guidance Values of Thermal Conductivity and Thermal Capacity.

Source: IDAE. Own elaboration.

Rock Type	Thermal Conductivity (W/mK)			Volumetric Thermal capacity
	Min.	Typical Value	Max.	(MJ/m3K)
Magmatic Rocks				
Basalt	1,3	1,7	2,3	2,3-2,6
Diorite	2	2,6	2,9	2,9
Gabbro	1,7	1,9	2,5	2,6
Granite	2,1	3,4	4,1	2,1-3,0
Peridotite	3,8	4	5,3	2,7
Ryolite	3,1	3,3	3,4	2,1
Metamorphic Rocks				
Gneiss	1,9	2,9	4	1,8-2,4
Marble	1,3	2,1	3,1	2
Metaquartzite		aprox. 5,8		2,1
Mica	1,5	2	3,1	2,2
Clay-shale	1,5	2,1	2,1	2,2-2,5
Sedimentary Rocks				
Limestone	2,5	2,8	4	2,1-2,4
Marl	1,5	2,1	3,5	2,2-2,3
Quartzite	3,6	6	6,6	2,1-2,2
Halite	5,3	5,4	6,4	1,2
Sandstone	1,3	2,3	5,1	1,6-2,8
Limolites and shales	1,1	2,2	3,5	2,1-2,4
Non-Consolidated Rocks				
Gravel, dry	0,4	0,4	0,5	1,4-1,6
Gravel, water saturated		aprox. 1,8		aprox. 2,4
Sand, dry	0,3	0,4	0,8	1,3-1,6
Sand, water saturated	1,7	2,4	5	2,2-2,9
Clay/Silt, dry	0,4	0,5	1	1,5-1,6
Clay/Silt, water saturated	0,9	1,7	2,3	1,6-3,4
Peat	0,2	0,4	0,7	0,5-3,8
Other materials				
Bentonite	0,5	0,6	0,8	aprox. 3,9
Concrete	0,9	1,6	2	aprox. 1,8
Ice (-10ºC)		2,32		1,87
Plastic (PE)		0,39		
Air (0-20ºC, dry)		0,02		0,0012
Steel		60		3,12
Water (+10ºC)		0,58		4,19

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