INTERNATIONAL ENERGY AGENCY

Implementing Agreement for a Programme of Research and Development on Energy Conservation through Energy Storage

Subtask A: Evaluation

Underground Thermal
Energy Storage
State of the art 1994

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UNDERGROUND THERMAL ENERGY STORAGE

State of the art 1994

The Netherlands Agency for Energy and the Environment

Swedish Council for Building Research

1995

Content

1. INTRODUCTION

Annex I of the "Implementing Agreement for a Programme on Research and Development on Energy Conservation through Energy Storage" concerns the State of the Art Report "Large Scale Thermal Storage Systems". The report dates from 1981. At that time, attention to the application of long-term thermal energy storage was almost wholly directed towards heat storage. Subsequently it has become clear that long-term cold storage is one of the most efficient applications of long-term thermal energy storage. The number of projects involving long-term thermal energy storage completed at the beginning of the eighties was still small. The 1981 State of the Art Report in many cases had to be based on data from feasibility and design studies. Today several dozens of projects have been realised that provide long-term cold and/or heat storage. Another major difference between the present situation and that some ten years ago, is that the economic motive to save energy has lost urgency, while the environmental benefits which go with energy saving have started to play a major part.

On the basis of the above, the Executive Committee of the Implementing Agreement for a Programme of Research and Development on Energy Conservation through Energy Storage concluded in mid-1993 that it would be desirable to draw up a new edition of the Annex I report. The representatives from the Netherlands and Sweden have taken it upon themselves to prepare the draft version of this State of the Art Report concerning long-term thermal energy storage. Representatives of other participating countries in the Implementing Agreement Energy Storage have agreed to comment on the draft report and where necessary to provide missing information. The present report is the result of these efforts.

To prepare this State of the Art Report, a large number of reports, congress papers, and articles in professional journals have been used. Whenever possible, use has been made of data from projects, using long-term thermal energy storage, which have been implemented. The main characteristics of some of these projects have been included in the appendix to this report. A deliberate effort has been made to present a wide range of projects with different applications and storage techniques. The information available makes it possible to draw general conclusions, so no really specific information has been included on storage techniques, applications or realised projects. For readers who desire more specific information, a bibliography with the most relevant literature has been included.

The authors hope that this revised State of the Art Report meets its goal, namely to give an up-to-date summary of the technical and economic aspects of the various long-term energy storage techniques, and even more important, of the application possibilities of these techniques.

2. THE APPLICATIONS OF UTES

2.1 General trends

Storing thermal energy can compensate a temporary imbalance between supply and demand or greatly reduce it.

Thermal storage for the short term (< 1 week) is implemented most. Examples are warm-water boilers in homes, and ice storage for air-conditioning plants in offices. Short-term storage systems lower the maximum demand capacity on the supply side. As a consequence, power companies can, for example, lower the maximum capacity setting and operate their power stations more efficiently. They stimulate the application of storage via rates (tariffs). Consumers will generally not save energy by short-term storage. The main objective of short-term storage is to compensate the imbalance between demand and available thermal capacity.

The application of seasonal thermal energy storage (>3 months) is currently much less common. This is not due to a smaller technical potential. On the contrary, there is a large amount of surplus heat in summer and surplus cold in winter. Further application is mainly delayed by economic factors, and to a lesser extent by technical ones.

In the past 15 years various applications of UTES (Underground Thermal Energy Storage) have been studied. Much attention has been given to the development of storage techniques. It appears that the development of a given type of storage technique greatly depends on local geological conditions. Therefore, for example, in areas without natural storage structures, small-scale storage systems in particular have been studied. The analysis of supply and demand systems has received little attention. Many well-functioning systems have been developed in the past few years which, however, have not been implemented to a great extent.

Furthermore, it is remarkable that attention in the initial years was primarily aimed at heat storage. The drop in prices of prime energy, and hydrothermal problems in storage have caused the number of applications of heat storage to be relatively small. Attention to the application of cold storage has greatly increased in the past few years, partly due to the increasing demand for cooling in buildings and the increased attention to environmental impacts caused by using chillers.

2.2 Applications studied

Applications of UTES are now reviewed. These concern the incorporation of storage into thermal energy supply and demand systems. How thermal energy can be stored is described in Chapter 3.

There are five main application groups:
- Cold/heat storage without heat pumps;
- Cold/heat storage with heat pumps;
- Heat storage with solar collectors;
- Heat storage with heat/power units;
- Heat storage in variable demand/supply systems.

Within the group a further specification has been made. The presented list of applications gives a reasonable impression, but is not intended to be complete.

The terms cold- and heat storage, which are used in this chapter, do not refer to a particular temperature level but to the objective: to cool or to heat.

2.2.1 Cold/Heat storage without heat pumps

The objective of this storage is to use winter cold in summer. In winter the store is charged with the help of natural cold sources. In some systems the stored heat from the summer is used for preheating in the winter. The cold extracted from the store in summer is used without further processing. Four main systems can be distinguished (Figure 2.1, legend see appendix I).

a This is the most common system configuration. In winter the cold store is charged with the help of a cooling tower or water cooler. In summer the cold which has been stored is used to meet a cold demand in the building, industrial or agricultural sector.

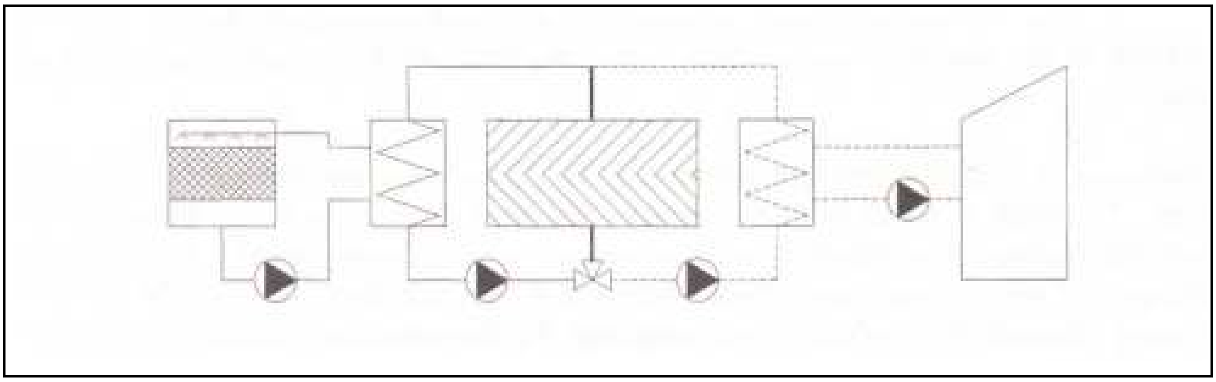

Figure 2.1a Cold/heat storage without heat pump

b A distinct system configuration of 1a is the system whereby the store is charged in winter by air handling units. Meanwhile the incoming air is preheated. An internal water circuit is cooled with outdoor air in these air handling units. The internal water circuit then transfers the cold by means of the heat exchanger to the external water circuit which flows through the store. In summer, ventilation air for the areas to be cooled is cooled by means of the air handling units. If it is cool enough outdoors, cooling is direct with outdoor air. Cooling with the use of cold from the store takes place when outdoor temperatures are high. This system is particularly applicable in the building sector.

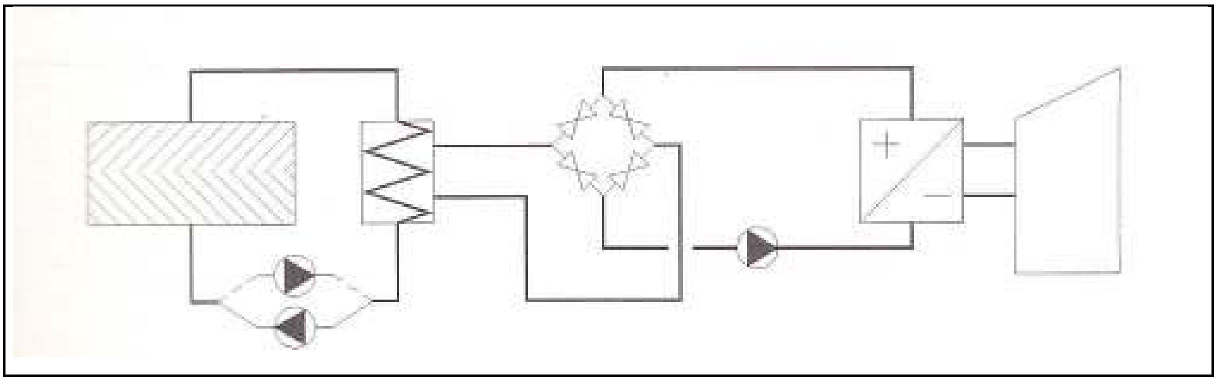

Figure 2.1b Cold/heat storage without heat pump

c This system uses winter cold stored in surface water, rainwater basins, etc. Industries with great cooling demands, particularly, can use surface water which offers considerable economic advantages in comparison to cooling towers.

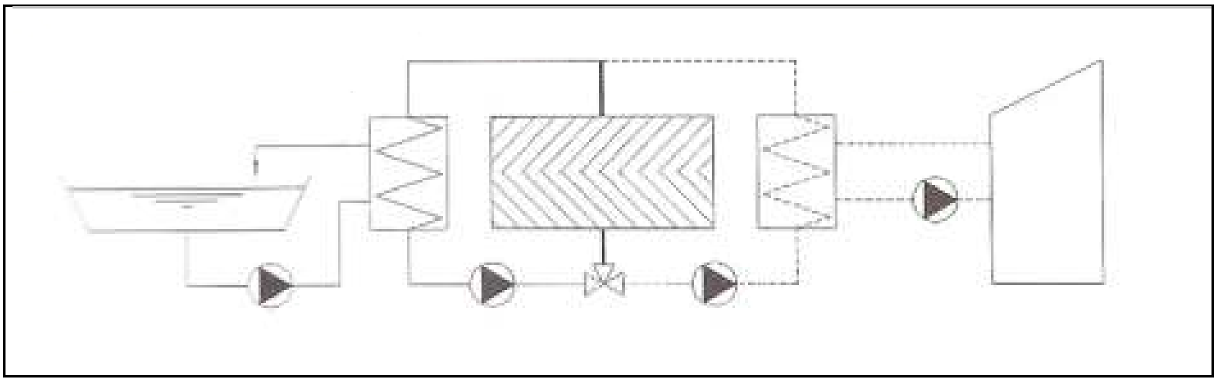

Figure 2.1c Cold/heat storage without heat pump

d If during a large part of the year, there is a cooling demand, and the natural temperature of the store is lower than the desired cooled water temperature, cold storage/recirculation can be applied. Heat obtained from the user in summer flows into the store uncooled. In winter, heated water is after-cooled before entering the store. On a yearly average, the aim is to obtain an entrance temperature equal to the supply temperature desired by the user. In fact, in this system, energy is not stored, but is conserved. This cold storage technique is used in agricultural and industrial applications.

Cold storage has application possibilities in almost every sector. However, the range between the supply and return temperature of the store and the required storage capacity vary greatly for the different applications (Figure 2.2).

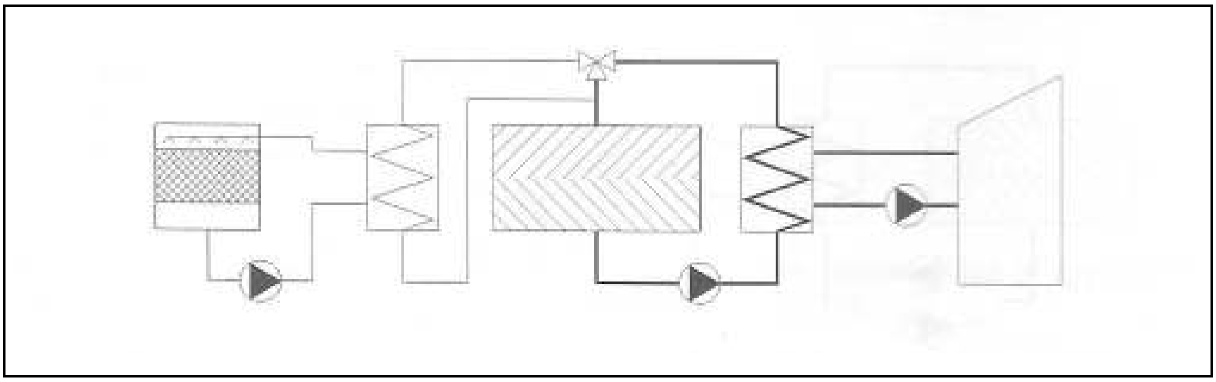

Figure 2.1d Cold/heat storage without heat pump

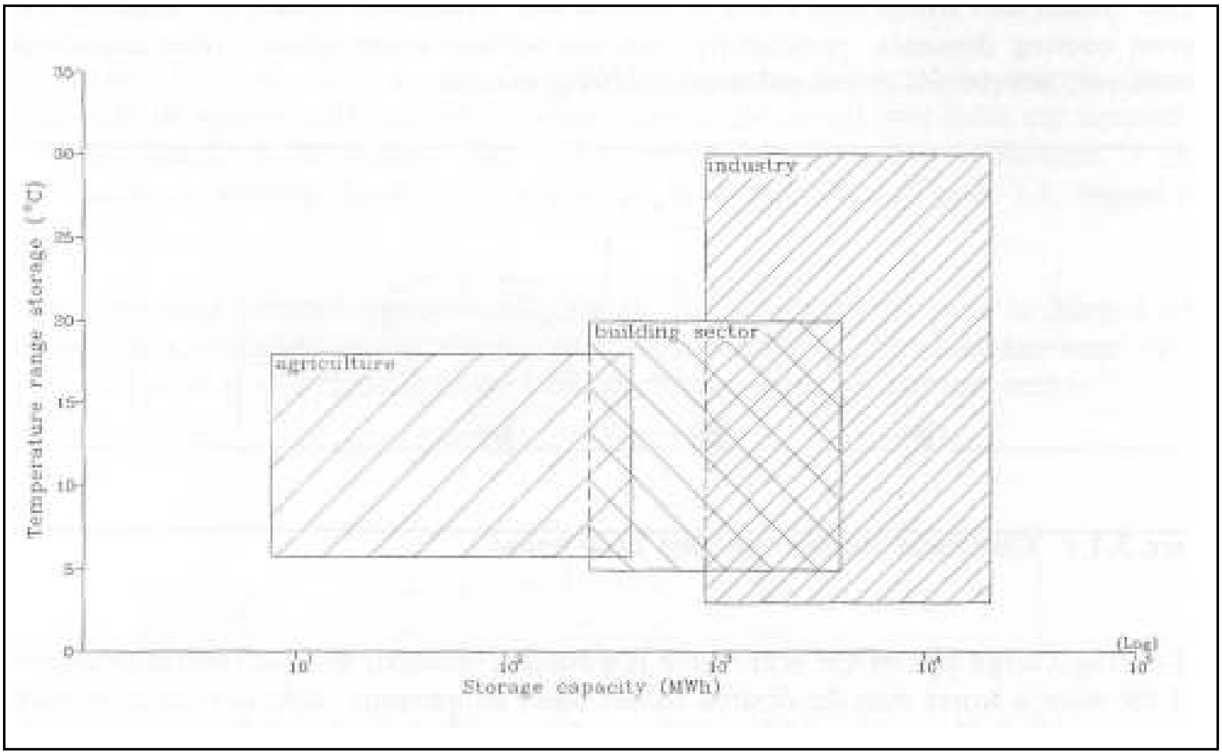

Figure 2.2 Applications of cold/heat storage without heat pumps

2.2.2 Cold/heat storage with heat pumps

The main objective of this type of storage is to improve the thermal efficiency for energy users who require both heat and cold. Storing and using the cold and heat which are generated during heating and cooling with a combined heat pump/chiller can be done with various system configurations (Figure 2.3).

a In winter the store is charged by using a heat pump for heating (usually heating rooms in a building). The vaporizer is heated by heat from the store. The heat pump is reversed in summer and acts as a chiller. The condenser is then cooled with cold from the store. The released heat is recharged into the store.

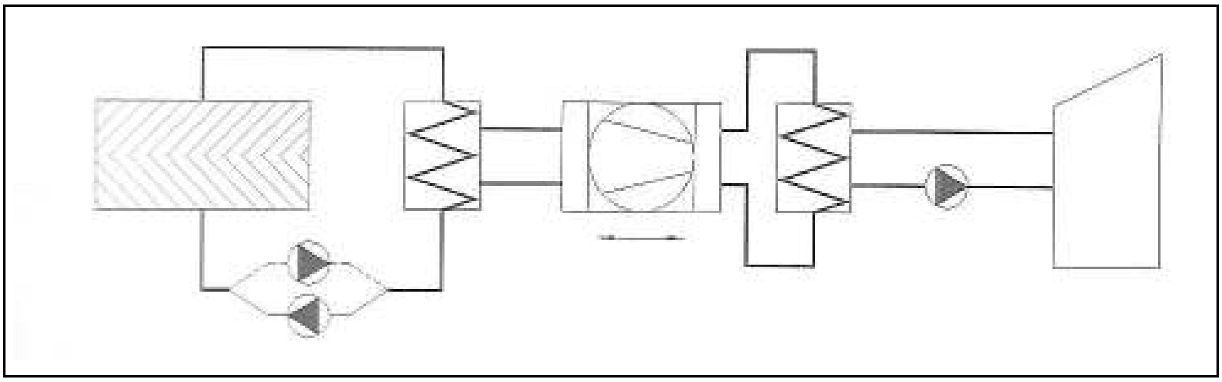

Figure 2.3a Cold/heat storage with heat pump

b The winter operation of this system is identical to system 3a. In summer however, there is no cooling by a chiller, but cooling is direct from the cold store. There are also systems in which at the beginning of the summer season, direct cooling takes place, while later during the summer, when temperatures in the store rise, the chiller is operated.

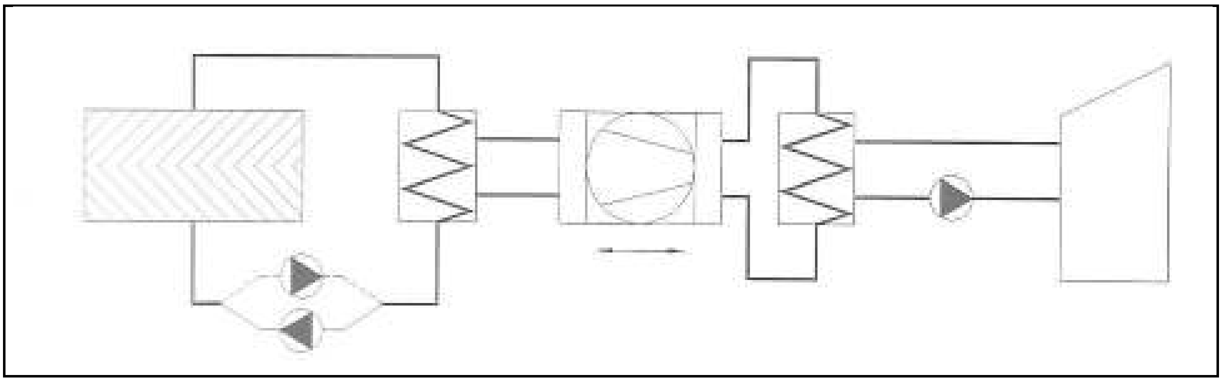

Figure 2.3b Cold/heat storage with heat pump

c If the supply temperature from the store to the vaporizer drops in winter, the COP of the heat pump deteriorates. In this system the outgoing temperature of the heat pump is kept relatively low, so that the COP remains at an acceptable level. However, to be able to use the heat, after-heating may be necessary in this case.

The application of cold/heat storage with heat pumps can be found in commercial buildings particularly. This can be explained by the fact that this is the only sector which has both a cooling and heating demand (Figure 2.4). Our data indicate that applications using cold storage without a heat pump are larger than those in which heat pumps are used. The temperature range between the supply and return temperature of the store is much greater than in cold storage without heat pumps. With some storage techniques the store can be charged to below freezing point (See Chapter 3).

In the agricultural and house-building sectors, heat pumps are also much used. However, here the cold generated is in general not effectively used.

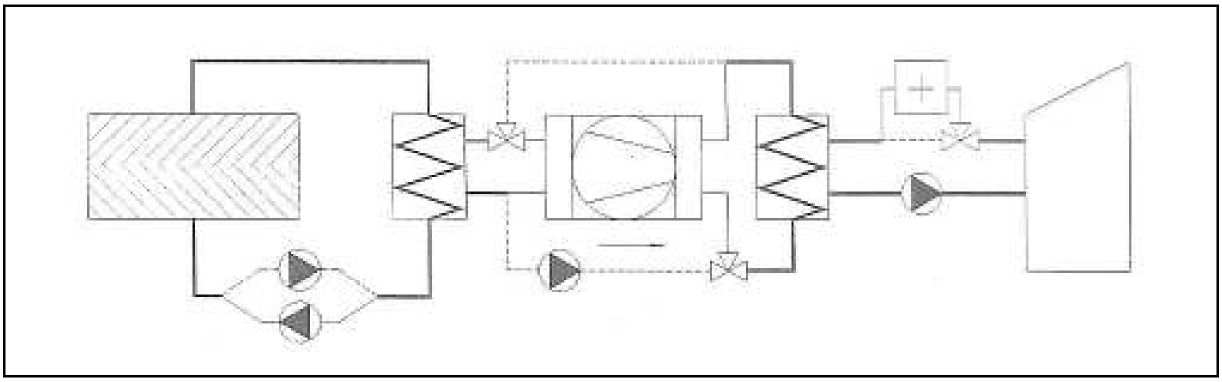

Figure 2.3c Cold/heat storage with heat pump

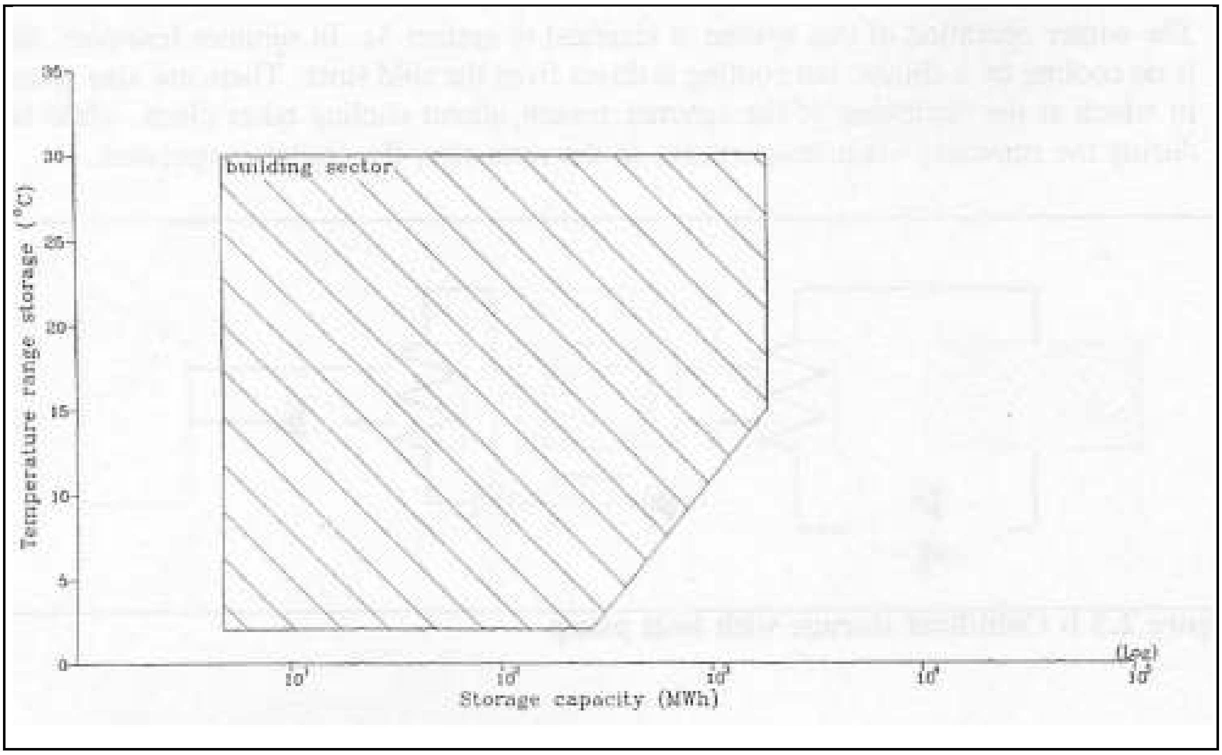

Figure 2.4 Applications of cold/heat storage with heat pumps

2.2.3 Heat storage with solar collectors

Storage can effectively transfer solar energy from intensive radiation and warm periods to cold periods with a low radiation intensity. Within the framework of the IEA Solar Heating and Cooling Programme (Task 7: Central Solar Heating Plants with Seasonal Storage), experience has been gained with this type of storage. Figure 2.5 shows a few of the systems used.

a The store is charged in summer by means of solar collectors. The storage temperature depends on the type of collector. The most frequently used type, the low temperature flat plate collector, gives a return temperature of about 60°C. With high-temperature flat plate collectors, temperatures of up to 100°C can be reached. In winter, the heat from the store is directly used for space heating. It is also possible to supply the user directly with heat from the solar collectors on sunny days in winter.

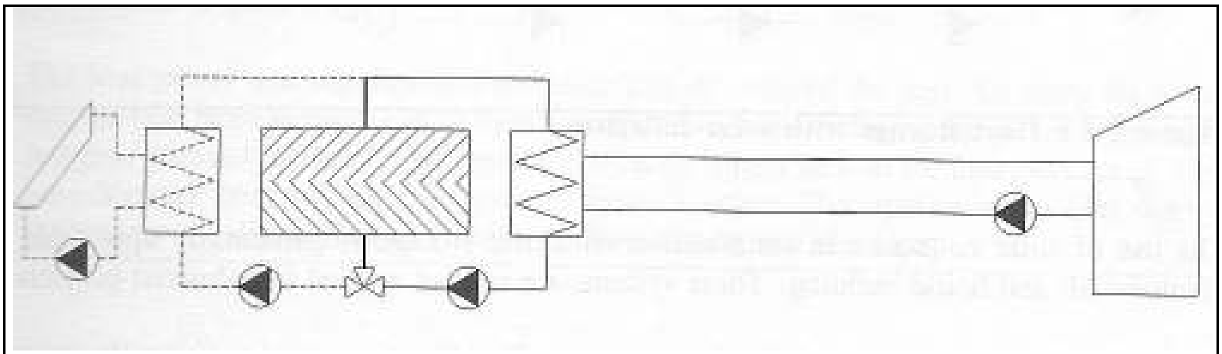

Figure 2.5a Heat Storage with solar collectors

b From studies on the use of solar collectors it appears that many systems cannot fully cover the heating demand. In this system the heated water is after-heated with a heat pump, which can be bypassed at the beginning of the winter season.

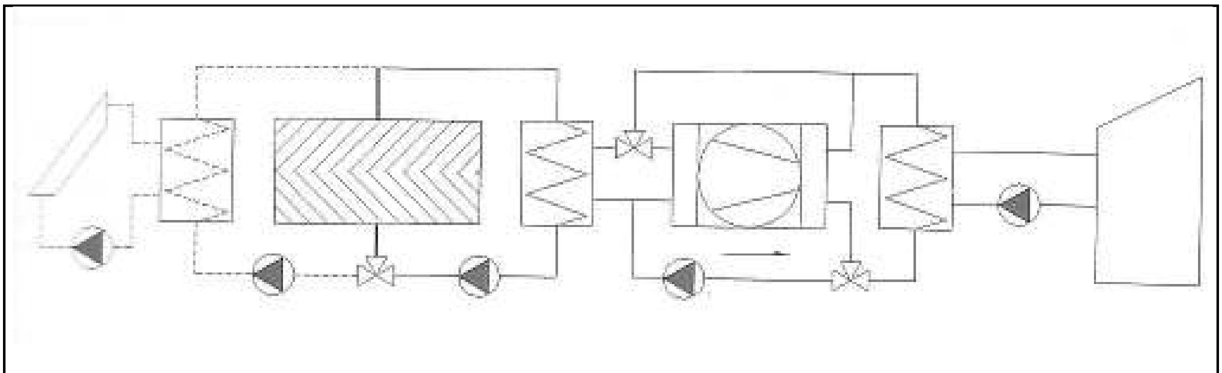

Figure 2.5b Heat Storage with solar collectors

c This system is comparable to system b; however, after-heating is done with a boiler. This method of heating does not influence the temperature in the store. The way after-heating is linked to the system varies for each project.

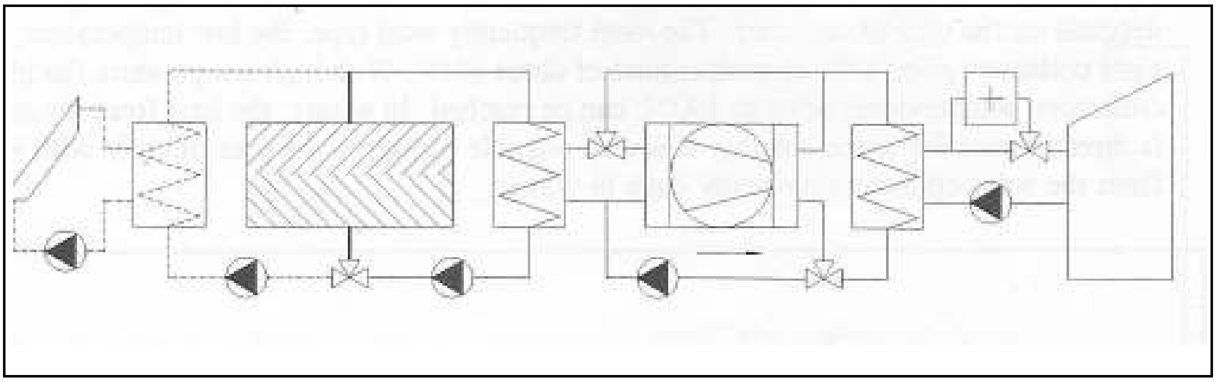

Figure 2.5c Heat Storage with solar collectors

The use of solar collectors in combination with heat storage is particularly applicable in commercial- and house building. These systems are not yet applied to industrial projects.

Figure 2.6 further analyses the application areas. The first two zones indicate the present application conditions. The third zone is based on only one large project in Sweden with the extremely high storage capacity of 58.000 MWh (Kungalu project, not yet realised). For the time being a capacity of several thousand MWh seems to be the upper limit. Comparison of solar energy storage with cold/heat storage indicates similar storage capacities but contrasting temperature differences. From the IEA study into the use of CSHPSS (Central Solar Heating Plants with Seasonal Storage), it appears that projects smaller than 500 MWh (zone 1) are not feasible due to the high investment costs and the poor storage efficiency.

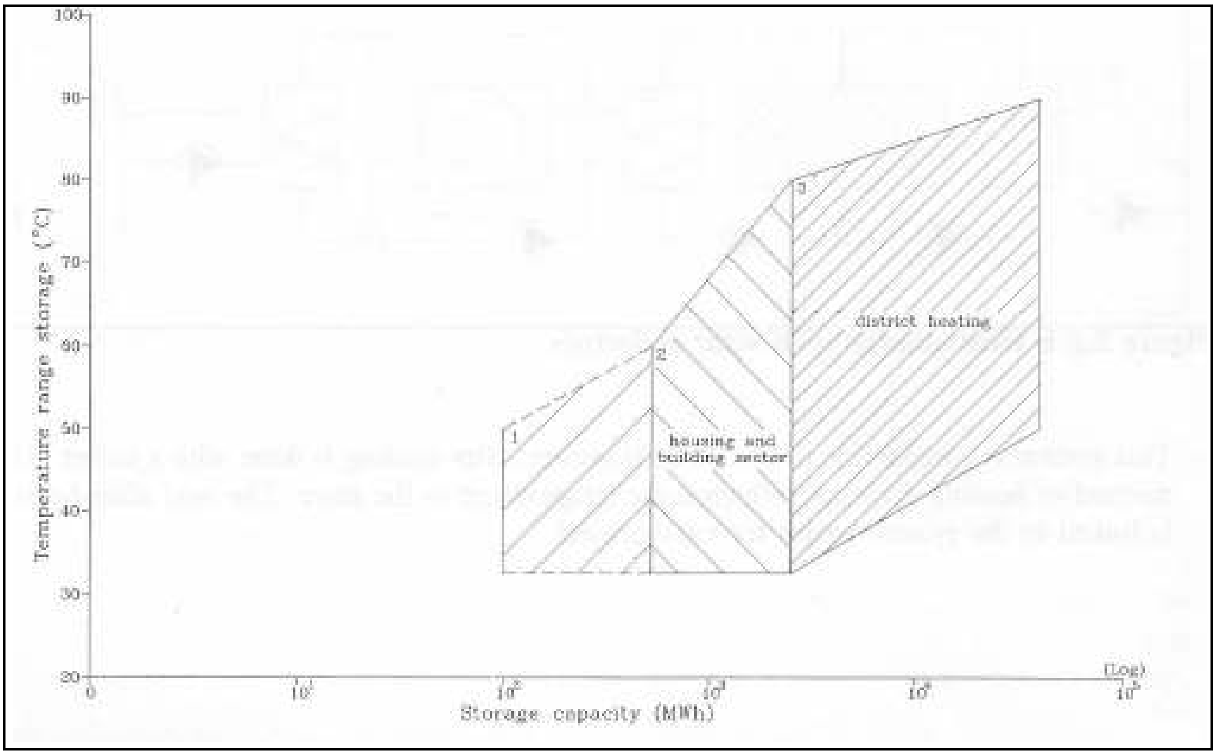

Figure 2.6 Applications of heat Storage with solar collectors

2.2.4 Heat storage with heat/power units

In comparison to the separate generation of heat and energy, combined heat/power generation can lead to some 30% saving of prime energy. Important in the application of heat/power co-generation units is the ratio between the heat demand and electricity demand. The optimum situation is that they are equal to that which is supplied by the heat/power unit.
The combination of heat/power units and heat storage is possible according to various system configurations (Figure 2.7).

a The heat/power unit supplies heat and electricity throughout the year. By using the store, surplus heat from summer can be usefully applied in winter. During the period when there is a heat demand the heat/power unit will directly supply heat to the user. In case of high heat demand, heat will also be extracted from the store. This application of heat storage overcomes the disadvantage of co-production of heat and electricity.

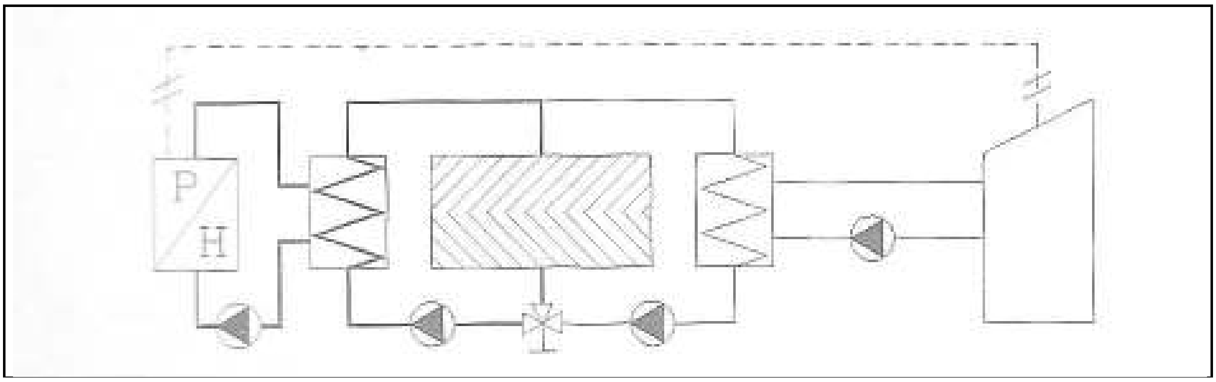

Figure 2.7a Heat storage with heat/power unit

b In this system an additional after-heating unit is installed for use in case of very high heating demands. The advantage of after-heating is that it can reduce the size of the co-generation plant installed, which is dimensioned on the basis of the electrical demand.

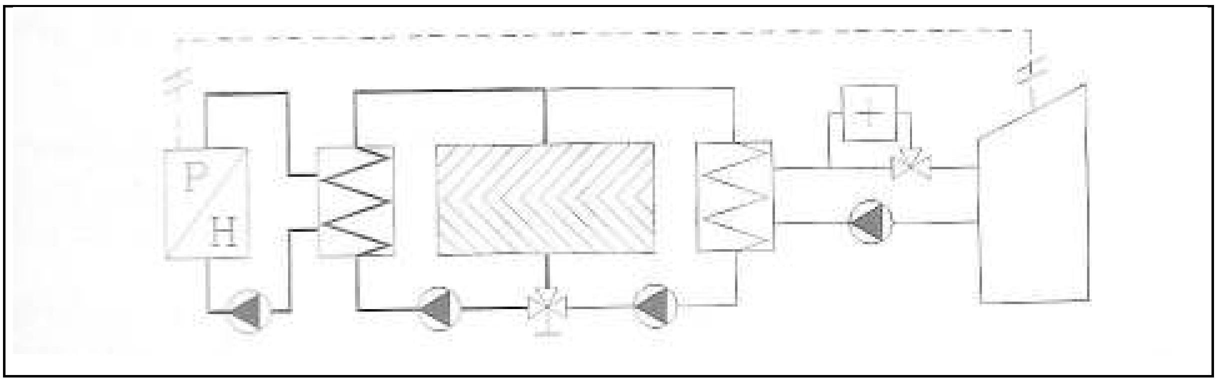

Figure 2.7b Heat storage with heat/power unit

Heat/power units are particularly well-suited to applications in commercial buildings.

The capacity of a heat/power co-generation unit is determined by the heating demand. The surplus electricity may be supplied to another user. The number of applications of heat/power with heat storage studied is small, so that the boundaries shown in Figure 2.8 are based on a limited amount of data.

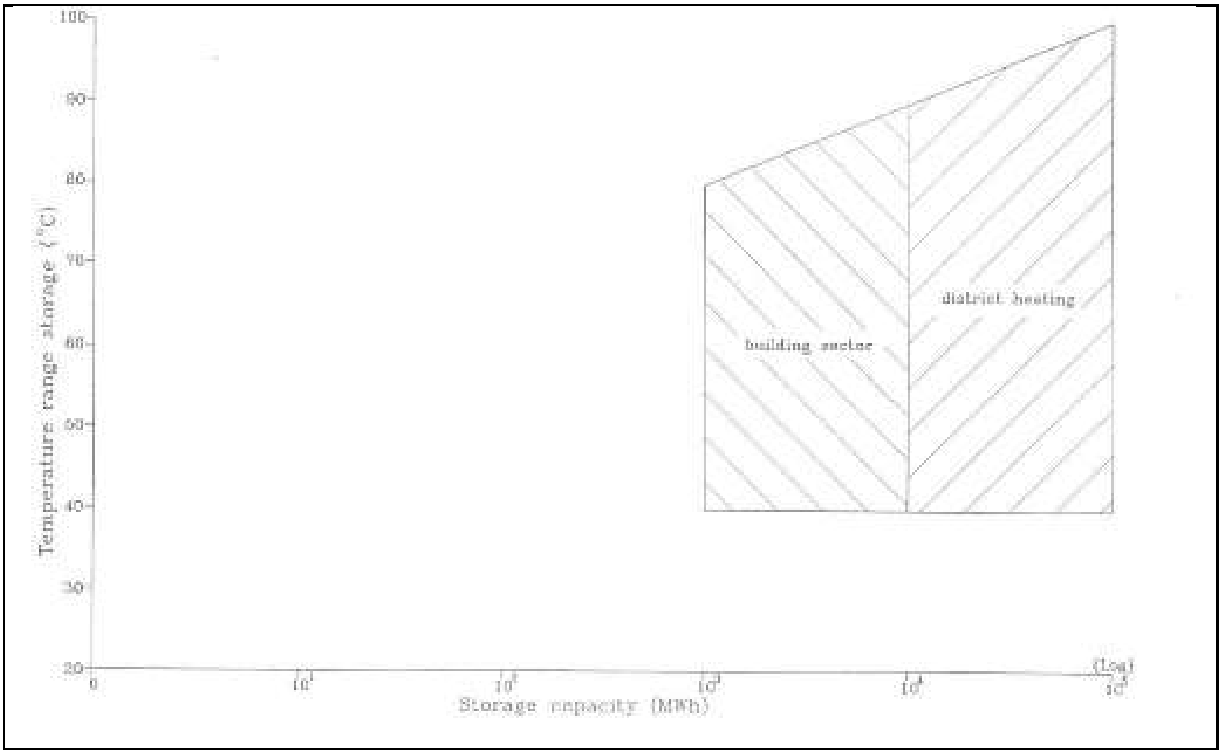

Figure 2.8 Applications of heat storage with heat/power unit

2.2.5 Heat storage in variable demand/supply systems

The systems described in the previous sections are based on the assumption that the user has generated the energy in the previous season. However, there are many sectors in which heat is produced without there being a useful or immediate application for it. Figure 2.9 shows a number of system configurations whereby surplus heat, by means of storage, can be economically applied by a different energy user.

a In this system, residual heat from industry is used to heat houses, offices or greenhouses. If the immediately available amount of residual heat is not sufficient to cover the heat demand in winter, the heat in the store has to be used. The store is charged in the period when there is no or little demand for heat.

b This system is based on the storage of heat released by electricity generation by a combined heat/power unit. This heat/power unit supplies electricity to the network and is owned by a power company. The heat stored is used in winter for the city heating system. If necessary the heat from the store is after-heated.

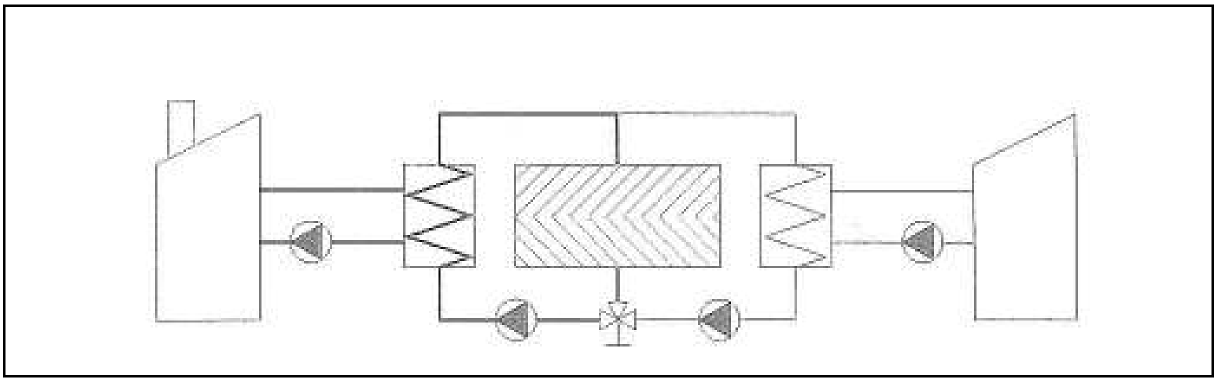

Figure 2.9a Heat storage in variable demand/supply systems

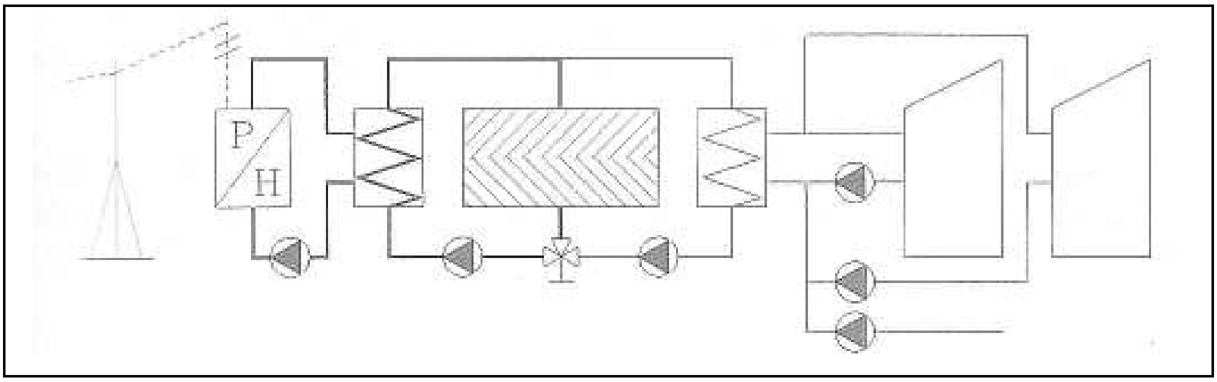

Figure 2.9b Heat storage in variable demand/supply systems

c Besides a combination of energy supplier and users, a combination of several users is also examined. These may be users who require different temperature levels or who have varying energy demands. For example, houses require relatively large amounts of heat but little electricity, while the opposite applies to offices. This makes a combination of housing and offices for the application of a heat/power co-generation unit attractive from the energy mviewpoint. Storage can bridge the imbalance between supply and demand.

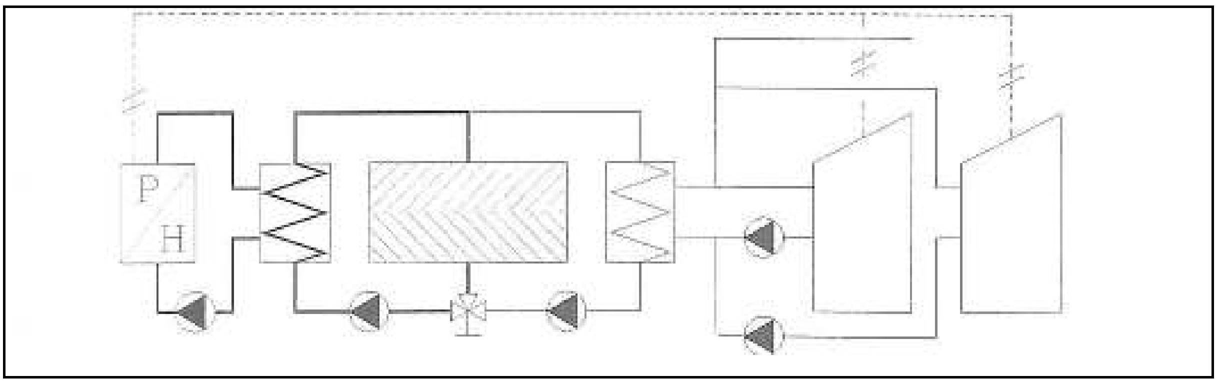

Figure 2.9c Heat storage in variable demand/supply systems

The application possibilities of heat storage for complex energy supply and demand systems are as yet barely recognised. Figure 2.8 shows that heat at temperatures between 40 and 120 _C and high storage capacities (> 10,000 MWh) are involved. Considering the large quantities of energy which are still discharged by industry, this application has excellent prospects.

2.3 Realised applications

The largest number of realised applications of long-term thermal energy storage can be found in Shanghai, China. As early as the late 60s, cold and heat have been stored in aquifers. From 1991 data it appears that 400 wells circulate 20.10^6 m^3 groundwater for cold storage (5-10 °C), while 130 wells pump 6.10^6 m^3 groundwater for heat storage (30-45 °C).
Storage of cold is applied for various industrial purposes and commercial buildings while heat storage is used particularly for greenhouses and in commercial buildings.

Tables 2.1 shows an extensive list of projects which have been implemented in IEA countries in the past 15 years. These projects have been realised for real objectives, not as research, and are still operating. In appendix II some projects are discussed in more detail.

Table 2.1 Projects realised in ANNEX 8 countries

Country	Location	name	Sector	Realisation	Storage technique	Major Energy Source	Hp	Storage task	storage volume (m^3)	Temp. warm (°C)	Temp. cold (°C)	flow (m^3/h)
Netherlands	Utrecht	RU	university buildings	1990	aquifer	waste	N	heating	100.000	90	40	100
Netherlands	Eindhoven	Heuvel Galerie	shopping centre	1992	aquifer	waste	Y	heating/cooling	200.000	32	18	100
Netherlands	Bunnik	BAM	office building	1993	aquifer	air	N	cooling	15.000	16	6	28
Netherlands	Zwolle	Provinciehuis	office building	1985	aquifer	air	N	cooling	70.000	20	9	60
Netherlands	Schiedam	Kantoorhuis	office building	1992	aquifer	air	N	cooling	20.000	15	6	125
Netherlands	Zoetermeer	IBM	office building	1993	aquifer	air	N	cooling	150.000	15	5	100
Netherlands	Gameren	Freesiakwekerij	greenhouses	1993	aquifer	air	N	cooling	80.000	12	12	50
Netherlands	HogeVeluwe	Museonder	museum	1993	aquifer	waste	Y	cooling/heating	5.000	12	12	5
Netherlands	Luttelgeest	Hederakwekerij	greenhouses	1993	aquifer	air	N	cooling	40.000	12	12	50
Netherlands	Utrecht	Jaarbeurs	events hall	1993	aquifer	air	N	cooling	70.000	14	7	400
Netherlands	Amsterdam	Perscombinatie	press	1987	aquifer	air	N	cooling	250.000	14	9	120
Netherlands	Gouda	Groene Hart	hospital	1992	aquifer	air	N	cooling	40.000	15	8	60
Sweden	Kungsbacka	Sunclay	school	1981	duct/soil	solar	Y	heating	80.000	16	10	
Sweden	Lomma	Lomma DH	houses	1990	aquifer	surface water	Y	heating	1.600.000	15	5	350

Sweden	Stockholm	GLG center	office	1988	duct/rock	waste	Y	heating/cooling	110.000	35	10	
Sweden	Solna	SAS	office	1987	aquifer	waste	Y	heating/cooling	500.000	15	8	700
Sweden	Klippan	Klippan DH	houses	1984	aquifer	surface water	Y	heating	600.000	16	8	150
Sweden	Kristianstad	Ericson Co	industry	1985	aquifer	waste	Y	heating/cooling	300.000	15	5	70
Sweden	Malmö	The Triangle	shopping center	1985	aquifer	groundwat er	Y	heating/cooling	200.000	25	10	40
Sweden	Malmö	Sparven	tele station	1991	aquifer	air/waste	N	heating/cooling	350.000	15	4	60
Sweden	Malmö	Hylie	tele station	1992	aquifer	air/waste	Y	heating/cooling	70.000	16	8	20
Sweden	Malmö	Dalaplan	tele station	1993	aquifer	air/waste	Y	heating/cooling	60.000	16	8	15
Sweden	Malmö	Sv. Radio	tv studio	1993	aquifer	waste	Y	heating/cooling	60.000	30	5	70
Sweden	Malmö	Elefanten	office	1994	aquifer	air/waste	Y	heating/cooling	150.000	17	8	30
Sweden	Malmö	Jägersro	tele station	1994	aquifer	air/waste	Y	heating/cooling	150.000	17	8	30
Sweden	Alnarp	Alnarp	greenhouse	1979	duct/clay	waste	N	heating/cooling	1.500	45	10	
Sweden	Kullavik	Kullavik	40 residential units	1983	duct/clay	solar	Y	heating	8.100	55	10	
Sweden	Söderköping	Söderköping	school, sport	1987	duct/clay	waste	Y	heating	36.0000	30	5	
Sweden	Utby	Utby	1 residential unit	1979	duct/clay	air	Y	heating	1.000	12	4	
Sweden	Finspång	Grosvad	750 residen-tial units	1985	duct/rock	solar/ waste	Y	heating/cooling	220.000	35	10	

Sweden	Finspång	Viberga	super market	1984	duct/rock	waste	Y	heating/cooling	42.000	30	15	
Sweden	Luleå	Lulevärme	office	1983	duct/rock	waste	Y	heating	120.000	65	30	
Sweden	Märsta	Märsta	40 residential units	1985	duct/rock	air	Y	heating	32.000	14	4	
Sweden	Sigtuna	Sunrock	1 residential unit	1978	duct/rock	solar	N	heating	10.000	40	10	
Sweden	Stockholm	Höstvetet	tap-water	1986	duct/rock	air	Y	heating/tap water	26.000	30	15	
Sweden	Krist. hamn	Capella	office	1988	duct/rock	air	Y	heating	120.000	90	75	
Sweden	Järfälla	ONOFF	office	1990	duct/rock	air	Y	heating	30.000	35	10	
Sweden	Falun	Hälsinggårdssk	school	1985	aquifer	surface water	Y	heating	35.000	35	10	
Sweden	Höllviken	Höllviken	telestation	1989	aquifer	waste	Y	heating/cooling	500.000	15	8	700
Sweden	Stockholm	Vallentuna	district heating	1984	duct/clay	surface water	Y	heating	20.000	20	8	10
Sweden	Solna	StoraSkuggan	recration centre	1984	duct/rock	surface water	Y	heating	1.440.000	14	3	1080
Sweden	Kristinehamn	Vintergatan	150 res. units	1990	duct/rock	air	Y	heating				
Sweden	Linköping	Lambohov	55 res. units	1980	rock pit	solar	N	heating	30.000	35	10	30
Sweden	Särö	Särö		1989	rock/pit	solar	N	heating	10.000	70	5	
Sweden	Gullspång	Gullspång	office	1982	tunnel	surface water	Y	heating	600	95	35	

Sweden	Kopparberg	Ljusnarsberg	district heating	1983	old mine	surface water	Y	heating	10.000	18	7	
Sweden	Avesta	Avesta	district heating	1981	rock cavern	waste	N	heating	180.000	38	5	
Sweden	Uppsala	Lyckebo	district heating	1983	rock cavern	solar	N	heating	15.000	115	40	
Sweden	Oxelösund	Oxelösund	district heating	1988	oil cavern	waste	N	heating	100.000	90	70	
Canada	Scarborough	Canada Centre	office	1984	aquifer	waste	Y	heating/cooling				
Canada	Winnipeg	Winpak	industry	1987	aquifer	air	N	heating/cooling		12	5,5	288
Canada	Ottawa	Carleton	university buildings	1989	aquifer	waste	Y	heating/cooling		9	9	120
Canada	Sussex	Sussex Hospital	hospital	1994	aquifer	waste	Y	heating/cooling	900.000	11	6	125
Germany	Wetzlar	UEG	office/lab	1992	duct/rock	waste	Y	heating/cooling		16	0	
Germany	Rathenow	Ophthalmica	industry	1992	duct/sand	waste	Y	heating/cooling		16	0	
Germany	Stuttgart	ITW	research	1985	gr/water pit	solar	n	heating/cooling	1050	35	5	
Germany	Linden	Geotherm plant	houses/office		duct/sand	waste	Y	heating/cooling		16	0	
Germany	Düsseldorf	Technorama	office	1990	duct/sand	waste	Y	heating/cooling		25	0	
Germany	Donauwörth	-	office/house	1989	duct/soil	solar	Y	heating	3.000	25	8	

3. STORAGE TECHNIQUES

3.1 Characteristics of a store

The various storage techniques can only be compared if their characteristics are clearly defined. The principal characteristics of a store are:
- the amount of energy that can be stored (storage capacity);
- the temperature during charging and discharging;
- energy losses in comparison to the capacity;
- investment and maintenance costs;
- useful life.

The amount of energy that can be held in a store is determined by the volume of the store, the storage medium and the temperature range. The amount of energy that can be extracted from the store, depends on the energy losses and the minimal (or maximal) temperature at which the energy can still be usefully applied.

The definition of the temperature difference depends on the type of store. Charge and discharge temperatures are not constant, the average temperatures during charging and discharging are used.

The actual volume of a store may be greater than the volume defined here. This particularly applies to aquifer storage in which there are separate warm and cold sides.

Storage media which can be used are: water (eg. cavern storage), unsaturated soil (e.g. bore hole storage), or saturated soil (eg. aquifer storage).

The thermal efficiency of a store is determined by the ratio between the extracted amount of energy and the amount of energy stored. The energy loss is the difference between amounts of stored and extracted energy. The total energy loss may be divided into two thermodynamic categories: energy that could have been retrieved efficiently at a high temperature; and energy at a low temperature that could only have been retrieved with difficulty. Thus thermal efficiency is determined not only by the energy system but also the temperatures used.

Energy loss is caused by conduction and convection losses. The magnitude of conduction losses is determined by the temperature difference between the store and its surroundings, the heat resistance between the store and its surroundings, and the surface area of the store volume. Good thermal insulation, reduction of the store's surface are a volume ratio, and raising (cold store) or lowering (heat store) the storage temperature are ways to restrict conduction losses and thus to increase storage efficiency.

Convection losses occur under the influence of flow of the storage medium, including flow as a result of density differences caused by temperature differences. This so-called boundary flow can be suppressed by storing warm water above cold water, or by creating additional flow resistance. Convection losses, for example, influence the storage efficiency of aquifer storage and sometimes of soil heat exchanger storage (see Section 3.4).
Storage techniques are often classified according to how the heat exchange takes place. The three categories to be distinguished are: convective storage, conductive storage, and mixed

storage. In the paragraphs below the various techniques will be described and their application areas indicated.

- storage medium water (convective)
  * rock cavern storage
  * pit storage

- storage medium soil (conductive)
  * vertical heat exchanger in unconsolidated soil or rock: duct storage

- storage medium ground (mixed, convective, conductive)
  * aquifer storage
  * gravel-water pit.

3.2 Convective storage

Convective storage systems work according to one of two principles.
The fully mixed store has a practically constant temperature within the store. This temperature profile is created by loading the store with warm water from the bottom or by heating the water in the bottom. The water is extracted from the top of the store.
The stratified store has a vertically stratified temperature profile. This store is loaded from above with warm water. Extraction is also from the top. High-temperature water can be extracted over a longer period from the stratified store than from a mixed store. A stratified store is always used for long-term storage because of the temperature profile and corresponding better thermal efficiency.

3.2.1 Pit storage

In a pit store, heat is stored as hot water. Pit volumes vary, usually from about 100 m^3 to a few 10,000 m^3. The relatively small storage volumes indicate that the store is used for short-term storage. The top of the store is usually at the ground surface and consequently the rest of the store is surrounded by soil or sometimes rock. The walls of the store are often sloped so that the bottom area is smaller than the top area of the store (figure 3.1). The store is always thermally insulated at the top and most of the time also at the bottom and walls of the store.
This type of store was developed to reduce the cost of cylindrical water tanks. The cost is reduced for two reasons:
- The construction could be made much weaker since the pressure of the hot water would partly be carried by the surrounding ground.
- The heat insulation could be reduced at the bottom and the sides because of the insulating surrounding ground.

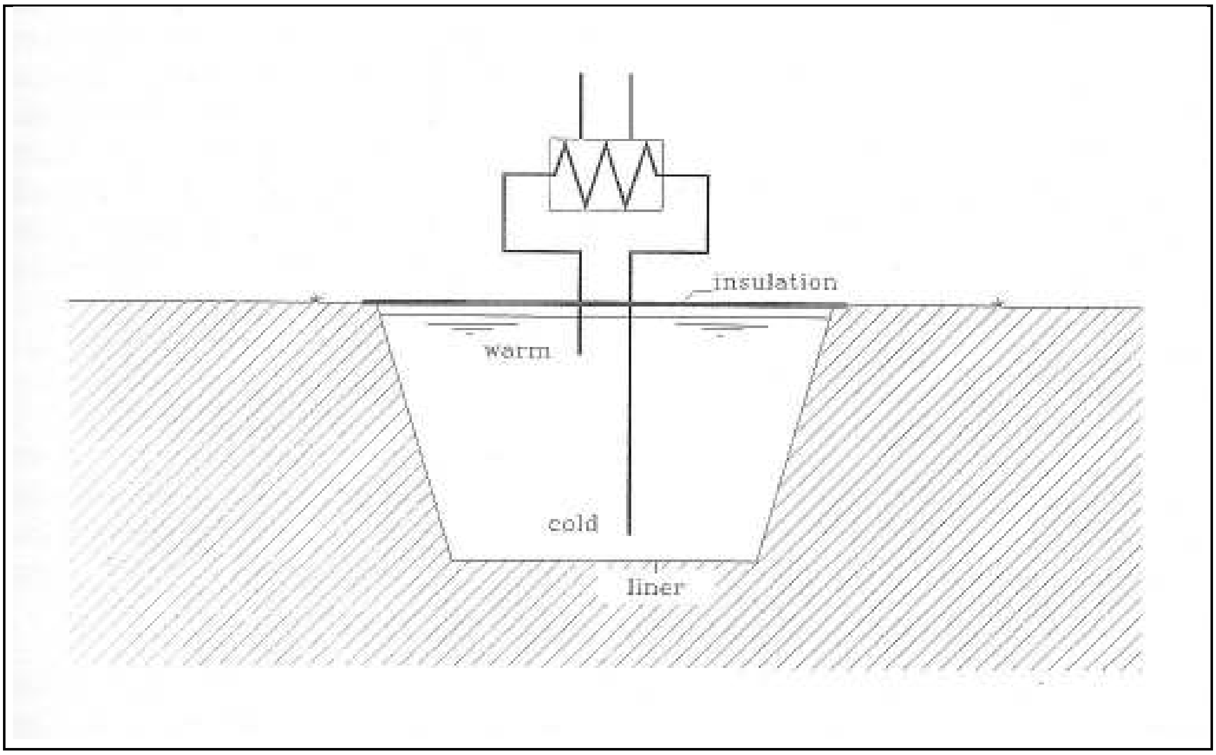

Figure 3.1 Pit storage

3.2.2. Rock cavern storage

In a rock cavern heat store, heat is stored as hot water in a large uninsulated rock cavern, as shown in Figure 3.2. Heat is supplied, in the form of hot water, to the top of the store, while cold water is pumped out from the bottom. When charging the store with heat, cold water from the bottom of the store is pumped to a heat exchanger, heated and returned to the top of the store.

Thermal stratification maintains the temperature difference in the store, with hot water at the top and cold water at the bottom.

When extracting heat, the flow is reversed, i.e., hot water is extracted from the top of the store and cooled water returned to the bottom. With careful design, the boundary zone between the hot and cold water can be kept quite thin. This zone moves up or down, depending on whether the store is being discharged or charged. Even if the store is almost empty (of heat), the remaining heat can still be extracted at high temperature.

The main advantage of this type of store is that the injection/extraction rate is limited only by the pumping capacity. This means that stores of this type can be used for both short term and seasonal heat storage.

The rock cavern heat store has two major limitations:
- The rock must be of good quality and
- Excavation costs are high.

The Lyckebo rock cavern (100,000 m^3 of water with a temperature up to 90 ^oC) for seasonal storage of solar heat has been in full operation since 1984. It became evident after five years of operation that the annual heat losses were up to 50% higher than those predicted assuming three-dimensional heat conduction in the surrounding rock. Claesson et al. (1994) concluded that the extra heat loss was due to a convective flow in a closed water loop through cracks from the top of the cavern to a transportation tunnel used during the construction and an expansion tunnel from the bottom of the rock cavern. The transportation tunnel winds down from the ground surface to the bottom of the cavern. The distance between the cavern and the tunnel is about 20 m. The Lyckebo experience shows that volume expansion should be undertaken by an independent system hydraulically isolated from the surrounding tunnels. It is also better to lead the transportation tunnel straight away from the cavern in order to avoid close contact between the tunnel and the cavern. This was done in the Avesta project where convective heat loss was found to be small.

3.2.3 Technical state of the art

In its simplest form, the pit store is a buried concrete or steel tank. It is a most reliable storage technique for short term storage of solar heat or heat derived from industrial applications. The high construction cost of the pit store is its major disadvantage. The cost of the pit store is about 30-300 ECU/m^3 depending on the volume of the store (Zinko, Hahn, 1994).

The rock cavern is a reliable storage technique for combined short term and seasonal heat storage. This type of store would work well for solar heat storage but because of the high construction cost new caverns are not built.
Recent research into convective storage has aimed at reducing the construction costs further by

using different liners of rubber, and steel. These liners are generally installed in pits with sloping walls, in many cases leakage problems have occurred.

There are advanced plans in Sweden to use an old oil storage cavern, in the city of Nynäshamn, for large scale seasonal storage of solar heat.

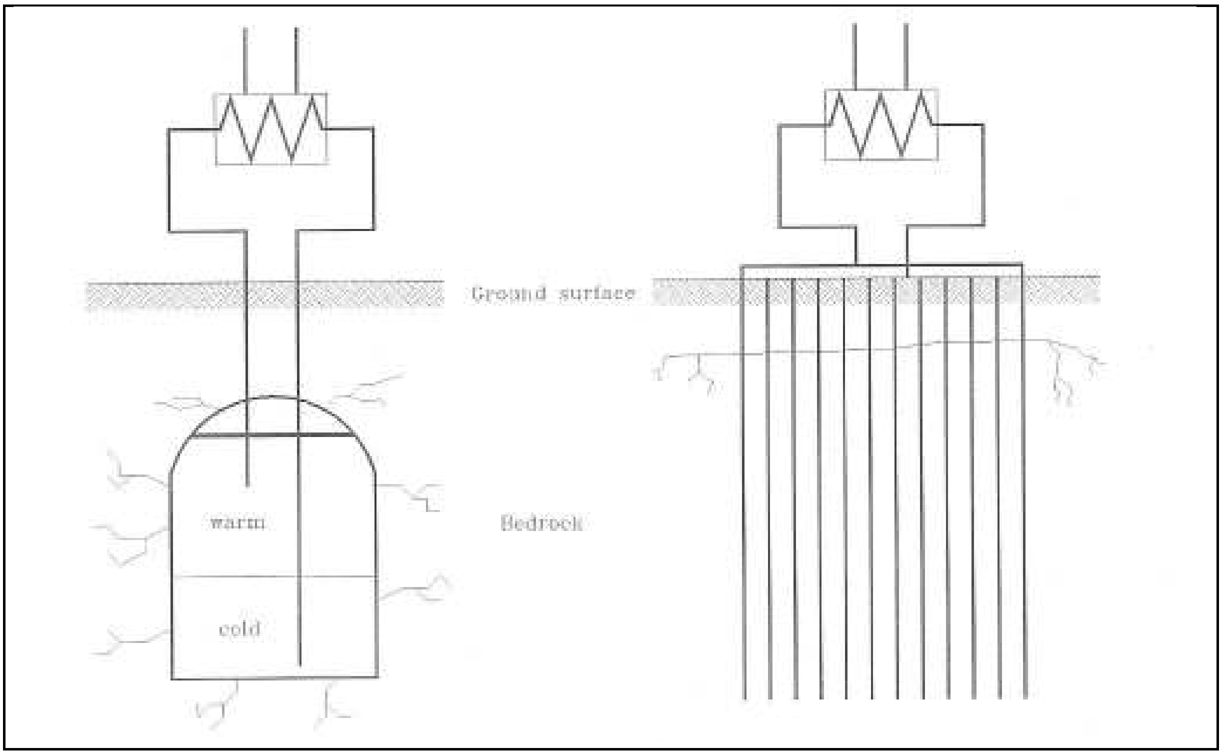

Figure 3.2a) Cavern Storage b) vertical heat exchanger

3.3 Conductive storage

In conductive storage, ground heat exchangers are used to transfer heat between the heat carrier and the ground. The heat exchanger often consists of a pipe system in the ground with liquid on the one side and ground on the other. The degree of saturation of the soil with water may vary

3.3 Conductive storage

In conductive storage, ground heat exchangers are used to transfer heat between the heat carrier and the ground. The heat exchanger often consists of a pipe system in the ground with liquid on the one side and ground on the other. The degree of saturation of the soil with water may vary from fully saturated to unsaturated. The greater the degree of saturation, the greater the heat capacity.
The ground surrounding the pipe system is gradually heated while the store is loaded (or cooled in case of cold storage) by the warm water flowing through the pipes. A characteristic of this storage technique is a gradual reduction of the temperature during discharging. Often conductive storage systems are provided with a heat pump because the temperature from the store during discharging may drop to below the directly usable temperature.

3.3.1 Vertical heat exchanger (duct)

There are two types of vertical heat exchanger systems: a closed pipe system into clay/sand; or boreholes in rock. The heat exchangers transfer heat from a heat carrier to the storage volume (see figure 3.2).
In solid rock the heat exchanger consists of a large number of boreholes, which are uniformly placed in the storage region. Vertical holes with 100-150 mm diameter and a spacing of about 4 metres have been used in most of the systems built. Sometimes the boreholes are drilled to form a diverging bundle with increasing hole spacing with depth. Each borehole has one or more flow channels for circulation of the heat carrier.
In clay or similar soils the systems are similar with vertical ducts of 100-150 mm diameter but a spacing of 1.5 - 2.5 m. For this type of soils the heat exchangers are driven into the ground.

- <u>Borehole with concentric inner tube</u>

The most simple arrangement of the flow channel is to insert a single plastic tube through which the heat carrier fluid is pumped to the bottom of the borehole. The region between the pipe and the borehole wall constitutes a channel for upward flow. The heat carrier fluid is pumped from the top of this channel to the main distribution system. The main advantage of this arrangement, the open system, is that the heat carrier fluid is in direct contact with the borehole wall. This provides a good heat transfer between the fluid and the surrounding rock.

- <u>Borehole with closed U-shaped loop</u>

The geohydrological and geochemical conditions at a specific site are often unfavourable for an open system. A common alternative is to provide a closed system by inserting one or more U-shaped loops of plastic tubing into the borehole. The base of the loops reaches the bottom of the borehole. The heat transfer from the heat carrier to the surrounding rock takes place via the plastic material and the filling material (usually water) of the borehole. This arrangement, which can always be used, results in a poorer heat transfer than the open system.

- Closed U-shaped loops in clay

In clay, sandy soil or peat deposits, the duct system can be obtained by driving down vertical U-shaped loops or thin plastic tubes. For seasonal stores in clay and sandy soil, the spacing between each ground heat exchanger is about 2 metres. The spacing is smaller then that for boreholes in rock mainly due to the lower thermal conductivity of clay. Ground heat exchangers with two U-shaped loops driven down together may also be used. In shallow deposits, a duct system may also be arranged by installing horizontal pipes in trenches.

3.3.2 Technical state of the art

The different types of vertical heat exchanger systems have all proved to be reliable during years of operation. The object of ongoing research is to reduce the cost of the construction and operation. This construction cost can be reduced by: optimizing the design; improving the borehole heat transfer and more efficient construction techniques. System operation can be improved by better system integration.

An optimization model, SmartStore, for borehole heat stores in rock and a similar model for clay and soil systems, TecoClay, will be available at the end of 1994. These models minimize the annual storage cost, ie. the annual costs of the investment, heat loss, maintenance and operation.

The heat transfer of borehole installations has yet to be fully examined. Natural convection in boreholes could improve the heat transfer considerably, especially important in high-temperature applications. Natural convection increases with the temperature gradient in the borehole and so, borehole pipe installations of materials such as copper should be tested.

A more efficient construction technique (less expensive) would be obtained if the drilling equipment was specially designed for heat store drilling. eg. drilling rigs that could drill 4 holes simultaneously. New drilling equipment has been developed, the G-drill, in the Kiruna mine, Sweden, which seems to be very promising for the future. The G-drill, which uses water instead of compressed air, more than doubles the drilling velocity in rock. This technique is however not yet available for deep boreholes.

The required system integration studies should include a seasonal heat store combined with a short term store to meet the daily variation of the heat load. This is also important during charging of solar heat, which varies strongly between day and night. With a short term store the seasonal store could be charged during the night also, which means a more efficient operation of the store.

With regard to market potential and feasibility, the most important system to develop is a high-temperature store connected to about 50 one-family houses with a low-temperature heating system, eg floor-heating of about 30°C. In such systems heat pumps would not be required.

3.4 Mixed storage

The principle of mixed storage is comparable to that of convective storage but the storage medium consists of saturated soil instead of water alone. Use is often made of natural water-bearing layers (aquifers). The groundwater can in principle also be used to transport the heat or cold for the user. The disadvantage of this is that the quality of the groundwater may change due to the influence of changing conditions (e.g. air infiltration) that, for example, may cause the infiltration system to clog up. Therefore, it is usual to separate the groundwater system from the user's water circuit by means of a heat exchanger.

3.4.1 Aquifer storage (ATES)

An aquifer is a water-bearing sand/sandstone layer, often confined at the top and bottom by a poorly permeable layer {(clay, peat, rock), (aquitard)}. The natural temperature of the groundwater in an aquifer depends on its depth and climatic conditions. Generally speaking, the natural shallow groundwater temperature lies between 0 and 20 °C. Under the influence of natural or artificial pressure differences, there is some groundwater flow in most aquifers. This flow can negatively influence the efficiency of storage.

An aquifer is a natural structure. To use this aquifer, access routes such as wells have to be constructed. Wells consist of vertical drilled holes provided with PVC or stainless steel screens within the thickness of the aquifer and with a PVC riser. The well is provided with an envelope of screen gravel, clay and supplementary gravel. The well contains a submersible pump to extract the water from the aquifer. All the water extracted is re-injected in the aquifer through another well.

How wells are located on the site greatly depends on the application for which the storage is intended. In figure 3.3 a number of well configurations are shown with the following characteristics.

- Single well

The system consists of a well (figure 3.3a) with two segments of perforated pipe. Warm groundwater is injected above the cold groundwater. To prevent great convective losses, it is desirable that where the warm and cold water divide, there is a poorly permeable layer. Given the fact that aquifers with a distinct horizontal divide seldom occur, single wells are not frequently used.

- Double well (cold storage)

The system consists of a cold well and a warm well (doublet) (fig. 3.4b). Both wells are provided with a submersible pump and injection system. The flow direction changes every season: in summer from cold to warm, in winter the other way around. The groundwater surrounding the cold well has a storage temperature below the natural groundwater temperature, and around the warm well it is higher.
The distance between the wells is such that thermal break-through in the aquifer cannot occur. The system can be expanded by placing a number of doublets next to each other.

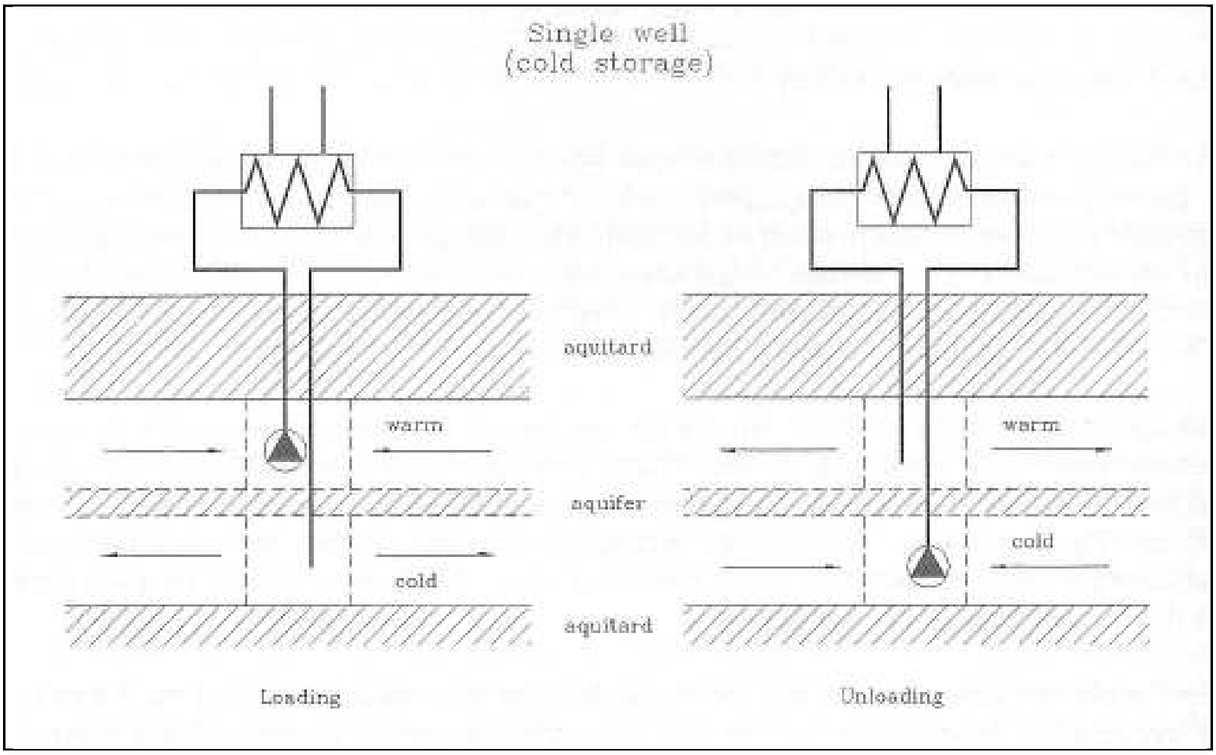

Figure 3.3a)   Single well ATES

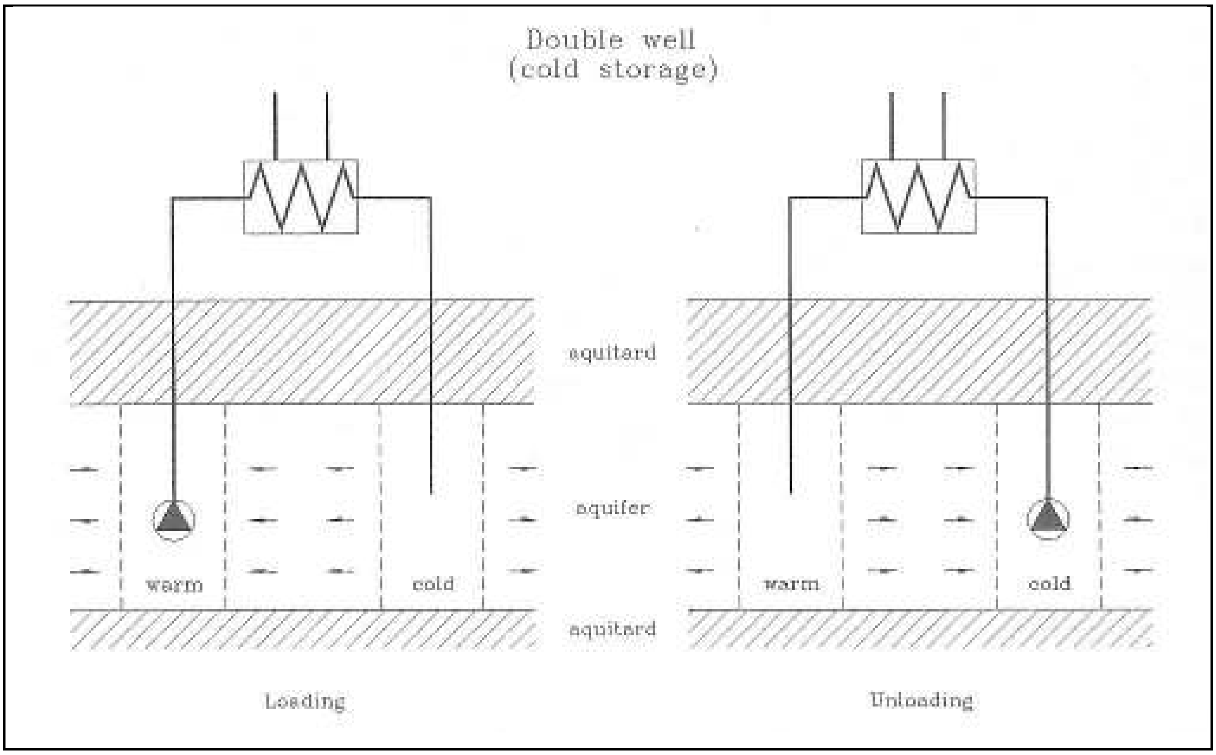

Figure 3.3b   Double well (cold storage) ATES

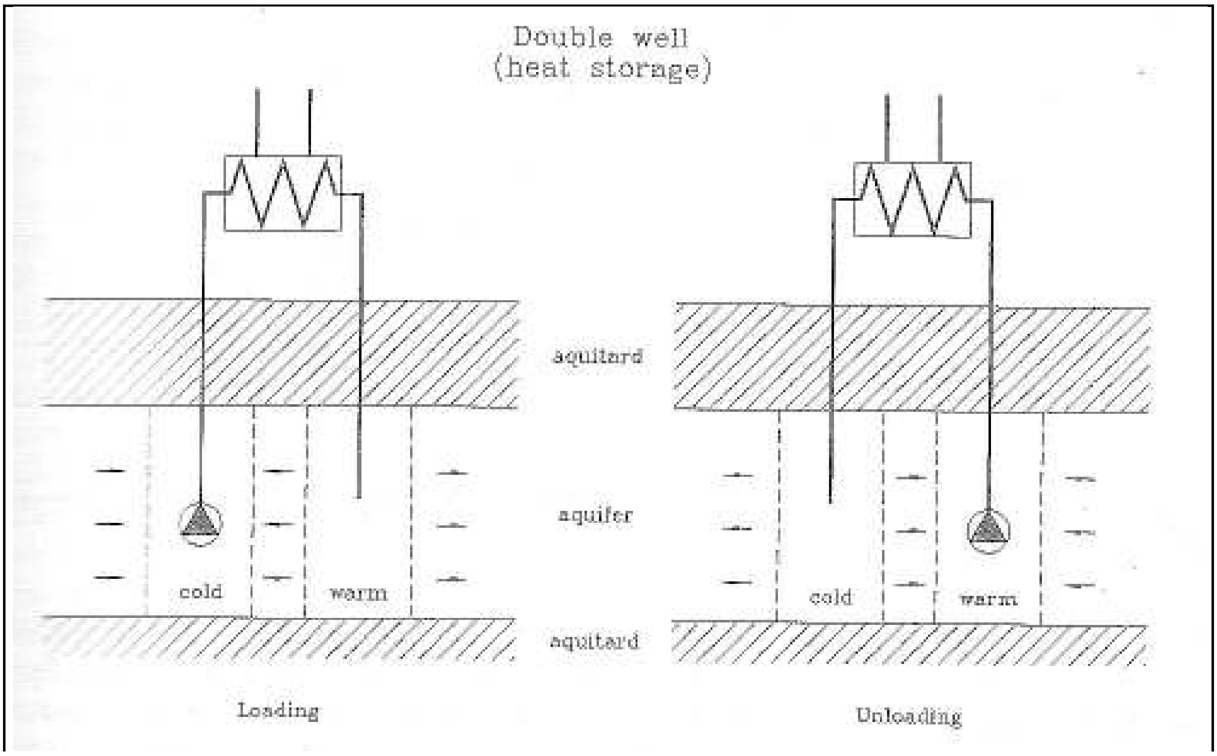

Figure 3.3c Double well (heat storage) ATES

- Double well (heat storage)

The system (figure. 3.3c) is comparable to the above system. A major difference is that both the temperature around the cold well as well as around the warm well are above the natural groundwater temperature. Therefore, in this system it is desirable to create a thermal break-through in order to limit heat losses. A problem with heat storage in particular is free convection. The warm groundwater flows to the top of the aquifer under the influence of the density difference created by the temperature differences. Free convection can be minimized by only using aquifers with moderate permeability; that is to say with a relatively great flow resistance. The most suitable aquifers for heat storage are those in which the vertical permeability is considerably lower than the horizontal permeability.

- Recirculation (cold storage)This system is based on a constant flow direction (figure 3.3d) Groundwater is extracted from the same well(s) throughout the year. In summer the groundwater is injected uncooled and in winter it is cooled before injection. The aim is to obtain a closed energy balance on an annual basis. This system is used by those who need cooled water with a temperature equal to the natural groundwater temperature (see also Figure 2.1d).

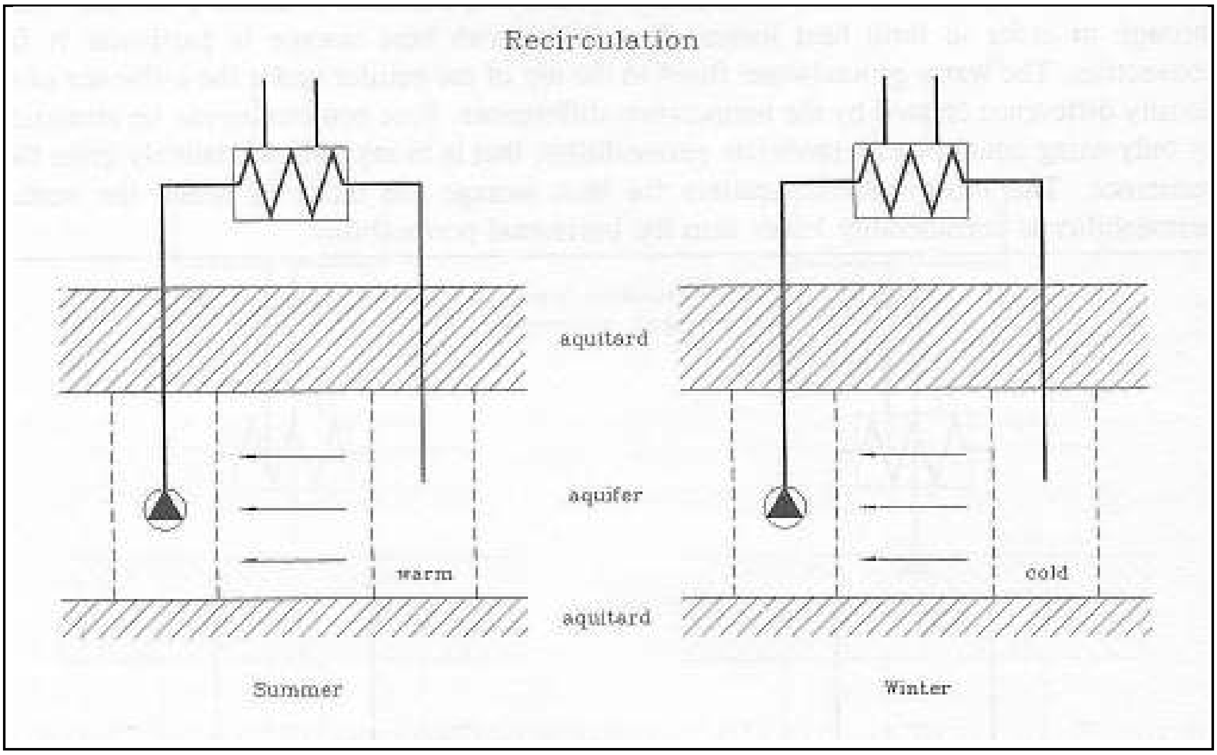

Figure 3.3d Cold storage recirculation ATES

The thermal capacity that can be supplied by aquifer storage is limited by the maximum amount of water to be extracted and injected. This maximum is determined by the permissable injection pressure, the permissable influence on the groundwater level, the permeability of the aquifer, etc. At present the greatest flow for one project applied, is about 700 m^3/hour. The storage temperature may vary from 0 to 150 °C. Temperatures higher than 100 °C are only possible in very deep aquifers.

The thermal efficiency of aquifer storage is determined by:
- size (capacity) and shape of the store;
- cut-off temperature in relation to storage temperature;
- storage temperature in relation to natural groundwater temperature;
- groundwater flow.

In long-term cold storage, efficiencies between 70 and 100% can be reached. The efficiency of heat storage is lower, 50-80%, due to greater conductive and convective losses. The maximum volume of aquifer storage is limited by the thickness of the aquifer, the spread of the aquifer, and the above-ground possibilities to install the wells. At present the largest storage capacity achieved is $3.5 \cdot 10^6$ m^3 water. The minimum volume is determined by economic and hydrothermal factors.

3.4.2 Technical state of the art

For cold storage and low temperature heat storage (maximum temperature about 40 °C) there are no technical problems to hamper large-scale implementation. The feared fast growth of micro-organisms, resulting in clogging of recharge wells, has not occurred in any of the projects which have been implemented. Only in laboratory experiments under very specific conditions has fast growth been observed. However, this aspect will continue to require attention in the coming years.

The above does not imply that cold storage or combined storage of heat and cold can always be applied without problems. The main technical problems which may occur in some projects are given below.

- The precipitation of Fe and Mn oxide is caused by a change in water chemistry. Shallow, unconfined aquifers generally have levels of Fe and Mn that are likely to yield oxyhydroxide precipitates if air is allowed to enter the ATES system. However, none of the processes causing Fe oxide precipitation need occur during injection if the system is air-tight, and the hydrology is controlled to eliminate the mixing of dissimilar waters near the well. For these reasons, the likelihood of Fe oxide clogging during injection is low in a properly designed system. If for any reason an air-tight system is not feasible, an iron removal method must be used.

- Chemical and electrochemical corrosion might occur. Chemical corrosion is induced by constituents such as CO_2, O_2, H_2S, dissolved sulphide, chloride, and sulphate. Electrochemical corrosion appears to be more frequent than chemical corrosion. Electrochemical corrosion is caused mainly by joining metals with different electrochemical potentials. Electrochemical corrosion also occurs on monometallic components that have been stressed, eg. welded joints, cut surfaces or damaged coatings. Usually it occurs in water that is slightly acidic and with total dissolved solids greater than about 1000 mg/L.

Protection against corrosion is in most cases dependent upon the choice of materials for each specific system. For instance, different steel alloys may cope with expected corrosion, as well as plastic materials, ceramics, or corrosion-resistant coatings.

Furthermore, the technical development in the years to come should be aimed at the integration of cold storage or combined storage of cold and heat into energy supply systems and on the regulation and protection which goes with them.

The main technical impediment to implementation of aquifer heat storage was for a long time the scaling of heat exchangers and recharge wells as a result of the precipitation of carbonates. Within the framework of Annex VI of the Implementing Agreement Energy Storage, a number of water treatment techniques were developed with which precipitation problems can be prevented or controlled without negative impacts for the environment occurring. These techniques have been successfully tested on laboratory or pilot scale. Before the implementation of high-temperature heat storage (storage temperature above some 60 °C) can take place in a technically responsible manner, it is necessary to implement a number of full-scale demonstration projects which apply the newly developed water treatment techniques.

Furthermore, in some heat storage projects, the same technical problems may occasionally occur as were mentioned for long-term cold storage. Because high-temperature heat storage is accompanied by greater soil temperature changes, the implementation of heat storage may sometimes have detrimental effects for other water- or groundwater users. In such cases interests will have to be weighed within the framework of the license procedures.

3.4.3 Gravel-water pit

If there is no natural aquifer, or if it may not be used, a gravel-water pit is an alternative option. This storage technique consists of a dug well which is filled with gravel or coarse sand (Figure 3.4). In the centre of the store there is a shaft from where pipes run through the store. At the top there is the warm water injection and extraction and at the bottom the cold water injection and extraction. The top of the store is thermally insulated. The walls and bottom are clad with a water-tight liner.

Charging and discharging of these stores is comparable with stratified tank storage. An advantage compared to tank storage is that free convection can be better suppressed. However, the disadvantage is that the storage capacity is about 50% lower due to the lower heat capacity of the filling material. Experiences with gravel-water pits are limited to a test facility in Stuttgart (Germany). This store has a volume of 800 m^3. The heat losses from the store are great, mainly through the walls. For large-scale applications construction with concrete partitions and outer walls is being studied.

The gravel-water pit is an special case of pit storage because a filling material is used. The remaining technical aspects are described in the section on pit storage.

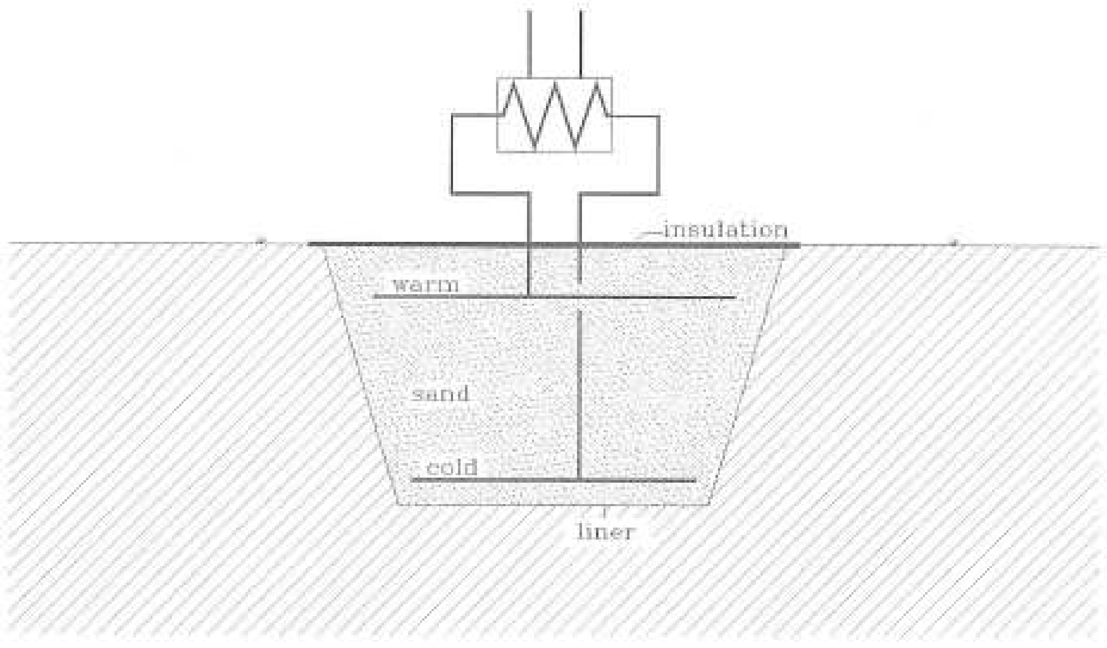

Figure 3.4 Gravel-water pit storage

3.5 Technical comparison storage systems

A number of storage techniques have been described in this chapter. All these techniques have, to varying degrees been developed into feasible products. There is also practical knowledge of many different market applications or attendant problems.
It is not easy to compare seasonal thermal energy storage techniques which are based on completely different concepts, in part because their characteristics are qualified in different terms. However, for the sake of a global comparison, a number of application-oriented parameters (storage volume, flow, temperature and efficiency) as well as some parameters determined by the specific local situation (geology, chemistry, space) have been scaled (low - high, unacceptable problems - no problems) in Table 3.1.
The terms used in Table 3.1 are briefly explained below to avoid subjective interpretations.

- **Storage volume**
  This scale is based on whether financial or technical problems will arise if the storage volume is expanded. Storage by means of cavern, vertical heat exchanger or aquifer use natural structures and are easier to expand than a man-made pit or gravel-water pit.
- **Flow**
  This scale is based on whether flow (m^3/h) can be increased without heat exchange deteriorating and/or the stratification of the store being disturbed. In conductive storage the flow can be simply increased but the heat exchange is limited by the physics of the diffusion process. Therefore, it would be better to replace the term 'flow' by the term 'kWh transfer potential'.
- **Temperature**
  Applicability in the entire temperature range (0-130 _C) is the criterion for this scale. The applicable temperature range is directly linked to geology in storage techniques that use natural structures.
- **Geology**
  Geology may be the decisive factor for applicability, particularly in techniques that use natural structures. Therefore an unequivocal scale is not possible for those techniques.
- **Chemistry**
  Problems with chemistry are usually directly related to the temperature levels at which storage takes place.
- **Space**
  This scale is based on the question of how much surface space the store requires and to what extent it can be integrated into existing or proposed surroundings.

There appears to be no storage technique which scores well on all factors. If we attempt to apply a gradation, then the applicability of the cavern, the aquifer and the vertical heat exchanger appears to be best if a large storage capacity is desired. Other techniques have fewer application possibilities, but this does not imply that in specific cases (often on a smaller scale) they will not perform to satisfaction. Furthermore, it appears that the freedom to choose a specific technique is to a large extent limited by the geohydrological situation.

The final choice of a storage technique will to some extent be determined by technical aspects. In the first instance an user will be looking for a cheap, reliable and efficient storage system, whatever the storage method may be. In Chapter 4 it will be shown that certain storage techniques, despite an outstanding system concept, have a poor future, mainly because of financial considerations.

Table 3.1 Technical comparison

	pit	cavern	vertical heat exchanger	aquifer	Gravel-water pit
storage volume	-	++	++	++	-
flow	+	++	0	+	0
temperature	0	+	0	+	0
efficiency	0	0	+	+	0
geology	+	--/+	0	--/+	+
chemistry	-	-	+	0	+
construction problems	-	+	0	+	-
space	-	+	0	+	-

-- very low, unacceptable problems
- low, major problems
0 moderate, some problems
+ high, minor problems
++ very high, no problems

4. STORAGE COST

4.1 Cost-determining factors

Thermal energy storage techniques as described in Chapter 3 always consist of a number of main components. The components applied vary greatly for each storage technique. The costs of these components in turn are determined by different factors, such as flow and capacity. In other words, the cost-determining factors per storage technique vary greatly. Besides the differences in main components, there are more differences between projects with long-term storage:

- operation: thermal efficiency;
- implementation method: with/without dividing heat exchanger;
- temperature range: heat or cold storage.

Together with cost variations per country, for example fuel and labour costs, the above differences give rise to an obscure cost composition. Therefore, it is impossible to compare the storage techniques by means of one relationship alone (costs/storage capacity).

In this chapter, the cost build-up of each storage technique is analyzed. Which components are cost-determining, how the costs of these components vary, and what causes them, are indicated. Causes are considered such factors as geological conditions, site conditions, energy volume, energetic capacity, and so forth.

In this chapter different currencies have been used; a conversion rates are given in table 4.1.

Table 4.1 Currency conversion rates

currency	ECU*
Dutch guilders	0.46
German Marks	0.52
Canadian Dollars	0.67
Swedish Crowns	0.11
American Dollars	0.89
France Francs	0.16
UK Pound Sterling	1.27

* based on exchange rates Amsterdam Currency Exchange Market, December 1993.

4.2 Convective storage

4.2.1 Pit store

The specific construction cost (SEK/m^3 or SEK/Kwh) of the pit store decreases with the storage volume. Zinko and Hahn (1994) investigated the total construction cost of the pit store. This cost was split-up into sub-costs from which Table 4.2 is derived. It is seen that there are three major sub-costs (liner, lid and other costs), which adds up to about 75% of the total cost.

The relative costs of the liner and the side insulation are reduced with increasing volume, because the plan area of the pit is reduced with increasing volume. The relative costs of the ground work and lid are increased with the volume.

Table 4.2 Relative Sub-Costs of a Pit Store

Storage Volume	5000 (m^3)	10000 (m^3)	20000 (m^3)	40000 (m^3)
Ground Work	6.5	7.9	9.9	10.2
Construction	10.4	10.3	10.4	10.8
Liner	25.3	22.8	20.6	19.0
Side Insulation	9.3	7.2	6.0	4.0
Lid	22.1	25.3	27.2	30.6
Other	26.5	26.5	26.0	25.3
Total	100.0	100.0	100.0	100.0

* Other includes costs for piping, planning, management and unforseen.

4.2.2 Rock cavern store

A parameter sensitivity study of the cost for seasonal storage in rock caverns was performed by Kjellson and Hellström (1994). The reference store has about the same size and operational strategy as the Lyckebo heat store. The height of the rock cavern and the distance between the cavern roof and the ground surface were both 30 m. The storage volume was about 100,000 m^3. Monthly values of the inlet fluid temperature and the flow rate were prescribed during injection and extraction of heat. The heat balance was calculated for 30 annual cycles, The water temperature in the store varies approximately between 30 and 90°C during one cycle. When parameters are varied, the storage volume is adjusted so that the amount of extracted heat remains the same as in the reference store., i.e. 5500 MWh. The heat cost is then calculated with a mortgage time of 30 years and a relative annual price increase of injected heat of 0%, in the reference case.

The construction cost has then been analyzed for different designs with estimates of the following sub-costs: design and preparation, blasting, heat transfer, administration, operation and amount of injected heat. The blasting cost, which covers 75% of the total investment cost, has been divided into four items and the relative costs for the reference case are: A/ establishing, entrance and transport tunnel (27%); B/ excavation and transportation of rock (61%); C/ crushing and disposal of rock (3%); D/ concrete injection and shaft to cavern (8%).

The pre-excavation costs in Item (A) are not dependent on the volume of the store. For small caverns this becomes a relatively high cost, which mainly consists of the cost for the transportation tunnel. The result of simulating the reference case shows that the heat cost will decrease with 6% when the tunnel length is reduced to half of the reference value.

The total excavation cost in Item (B) is dependent on the store volume. The cost per m^3 decreases with larger caverns. The blasting cost may also be lower during periods with few other competing construction activities in the area. When simulating a 20% increase or a 20% decrease respectively of blasting cost per m^3, the heat cost will change about 6% , See figure 4.1.

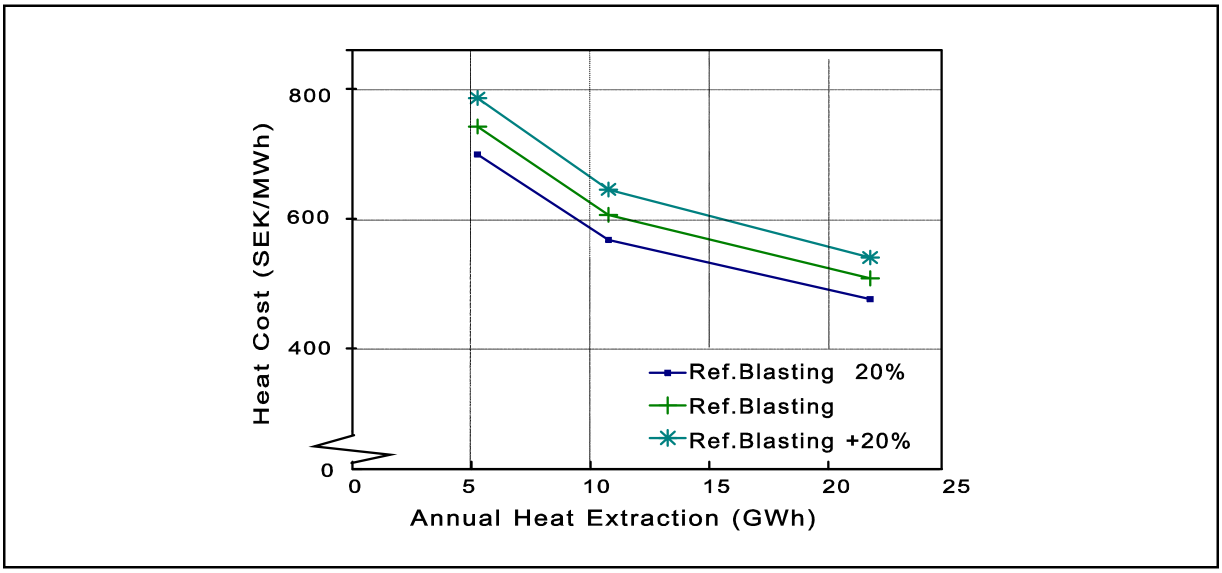

Figure 4.1 Heat cost as a function of average annual heat extraction for different blasting costs

Item (C), crushing and disposal of rock can be a cost or an income depending on the possibilities of selling the crushed rock. Compared to the reference case, the heat cost changes by about 7% between the simulations, i.e. with an income of 20 SEK/m^3 and a cost of 10 SEK/m^3 for the crushed rock. Item (D) is dependent on the volume and the rock quality.

The heat cost for the reference case was also studied by varying the cost of the injected heat and the relative cost increase for the extracted heat. As seen in Fig 4.2 these factors have a large influence on the heat cost. For the reference case (100,000 m^3, 5500 MWh) , the estimated heat cost is about 740 SEK/ MWh, the specific construction cost is 5.1 SEK/kWh, that is 280 SEK/m^3. In the case of a four times larger heat load (22000 MWh) a storage volume of 380,000 m^3 is required. Here the estimated heat cost is 510 SEK/MWh, which results in specific costs of 2.8 SEK/kWh and 160 SEK/m^3 respectively.

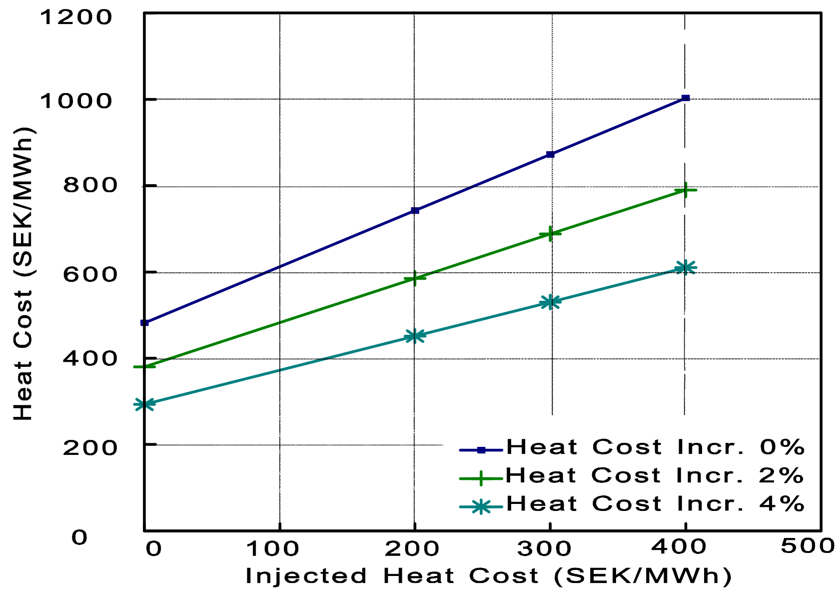

Figure 4.2 Heat cost as a function of injected heat costs for different relative annual price increase of extracted heat

4.3 Conductive storage

4.3.1 Vertical heat exchanger

Nordell (1994) evaluated the construction cost of the borehole heat store as a function of a large number of parameters (e.g. the soil depth, thermal properties of rock and soil, heat extraction capacity, storage temperature and a large number of cost data).

The optimization model SmartStore was used in the parameter analysis. This PC-based model calculates the design that results in the minimum annual storage cost. The annual storage cost was defined as the sum of the annual costs of the investment, heat loss, operation and maintenance.

The parameter study was performed based on a reference storage design, considered state-of-the-art in 1991, During the analysis this design was calculated as a function of the parameter under investigation. Only the studied parameter was varied while other data: technical, operation, climate and cost data were equivalent to those of the reference store.

The optimum design is mainly given as the number of boreholes, borehole spacing, borehole depth and required heat injection to fulfil the storage task. From these values other storage data are calculated e.g. storage volume, land area, etc.

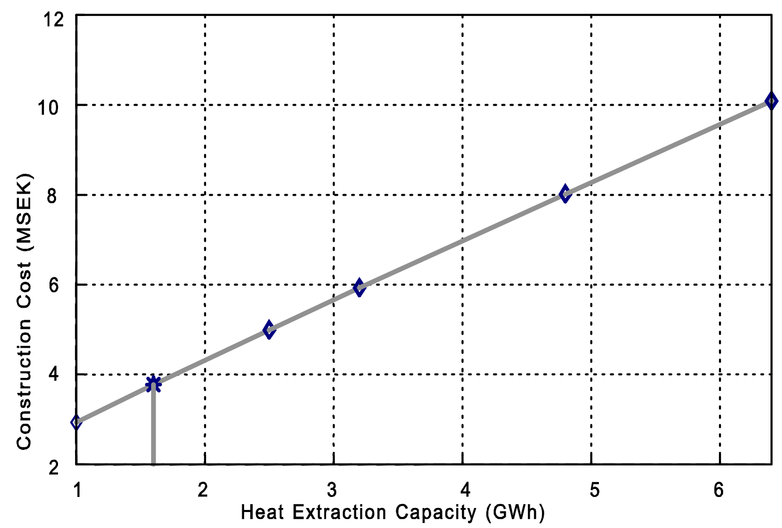

Figure 4.3 Optimum construction cost as a function of heat extraction capacity

The cost of the borehole heat storage system could roughly be divided into three parts; drilling, piping and miscellaneous cost. The drilling cost is about 40% of the total construction cost.

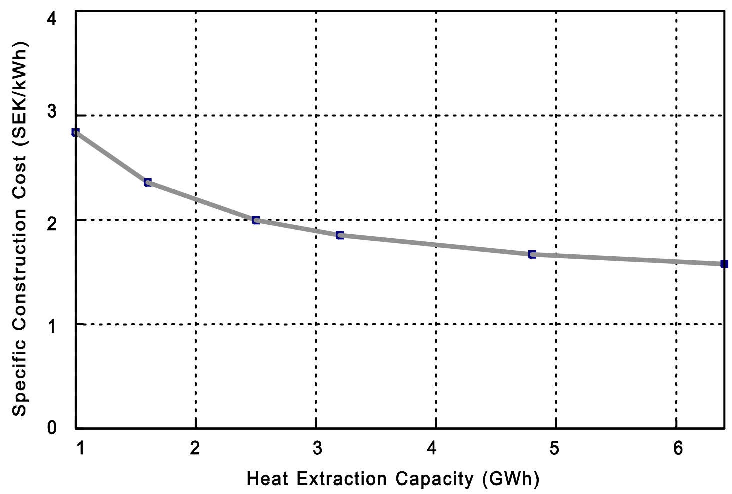

Figure 4.4 Optimum specific construction cost as a function of heat extraction capacity

It was found that the construction cost changes linearly with increased heat extraction capacity, figure 4.3. This construction cost was recalculated to show the specific construction cost, e.g.

the construction cost per annually extracted heat, figure 4.4. It is seen that the specific construction cost is approximately 1.50 SEK/ kWh (0.17 ECU/kWh).

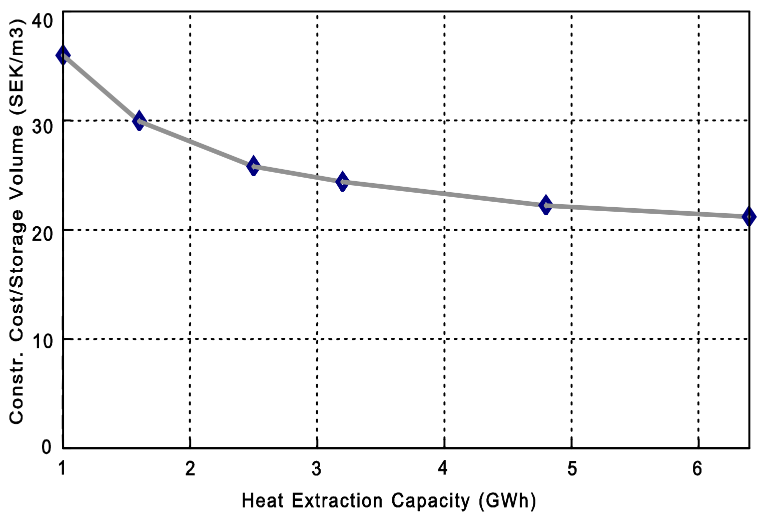

Figure 4.5 Optimum volumetric construction cost as a function of heat extraction capacity

Another commonly used parameter, is the volumetric construction cost, i.e. the construction cost per storage volume, figure 4.5. The store becomes more cost effective as a function of increasing size, measured as volume or capacity. The volumetric cost is approximately 20 SEK/m^3 (2.2 ECU/m^3) for a 7 GWh store.

4.4 Mixed storage

4.4.1 Aquifer storage

IF Technology (1994) evaluated the cost of aquifer storage in the Netherlands.
If aquifer storage is roughly outlined, four main components result: wells, pipes, heat exchanger, and water treatment. The regulation and protection of the store are considered part of the building installations because these functions are usually integrated in the building installation regulation and security system. Table 4.3 shows which factors determine the costs of these four main components.

Table 4.3 Cost components aquifer storage

component	Cost-determining factor	cause
wells	depth	geology
	diameter	groundwater flow
	number	groundwater flow
	material	temperature
pipes	length	amount
	diameter	groundwater flow
	material	temperature
	material	water composition
heat exchanger	size	groundwater flow
	size	temperature
	material	water composition
water treatment	size	groundwater flow
	type of treatment	water composition
	type of treatment	amount

The cost structure indicates that the costs for each main component, besides a number of location-bound factors, are for a major part determined by the maximum groundwater flow. The storage volume (capacity) plays a minor role as far as investments are concerned. The latter is due to the fact that aquifer storage uses a natural structure which is generally not limited.

The cost structure has been worked out in figures on the basis of the above. Herewith the flow is used as base and the band width is determined by geology and the capacity.

Table 4.4 Cost composition

base	parameters	band width	
	temperature	geology	quantity
flow (25 - 500 m^3/h)	low (< 50 °C)	shallow (0 - 50 m)	small (25.000 m^3)
	high (> 50 °C)	deep (150 - 200 m)	large (see text)

The parameter 'large' given in Table 4.4 depends on flow. This value is determined by the maximum volume of groundwater to be pumped up in a half year. For 25 m^3/hour and 500 m^3/hour this means respectively $0.1 \cdot 10^6$ m^3 and $2.2 \cdot 10^6$ m^3.

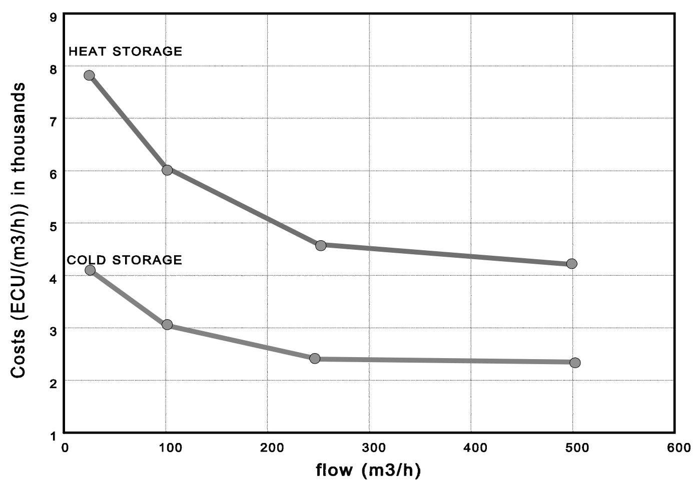

Figure 4.6 Specific investment costs for cold and heat storage against flow

In figure 4.6 the specific investment costs for cold and heat storage are plotted against the flow. The costs are exclusive of the costs for regulation and security, and exclude design costs. The main cost-determining factor besides flow is temperature. At high temperatures additional provisions have to be made, such as water treatment, insulation of transport pipes, and stainless steel risers and filter tubes in the well. Generally the costs for heat storage are twice as high as for cold storage.

The specific costs for cold storage rapidly decrease with increasing flow. The costs stabilize from 300 m^3/hour at a level between 1500 and 3000 ECU/(m^3/h). The band width is practically independent of flow and amounts to 1500 ECU/(m^3/h). The curve of the specific costs for heat storage has the same trends as that for cold storage. However, costs do not stabilize until a flow of 500 m^3/hour at a level between 2500 and 5000 ECU/(m^3/h). The band width decreases with increasing flow.
In practice, one is often interested in investment costs per storage volume of water or energy. Although, as stressed earlier, this parameter for aquifer storage does not give a correct picture. However an attempt is made in figure 4.8, where the price per stored volume of water is given for a system with a flow of 250 m^3/hour. The price varies between 14 and 3 ECU/m^3 for cold storage and between 30 and 5 ECU/m^3 for heat storage.

- Gravel-water pit

The number of gravel-water pits actually realised is so small that a good cost analysis cannot be made. The very small-scale project (800 m^3) in Stuttgart (Germany) cost 260 ECU/m^3.

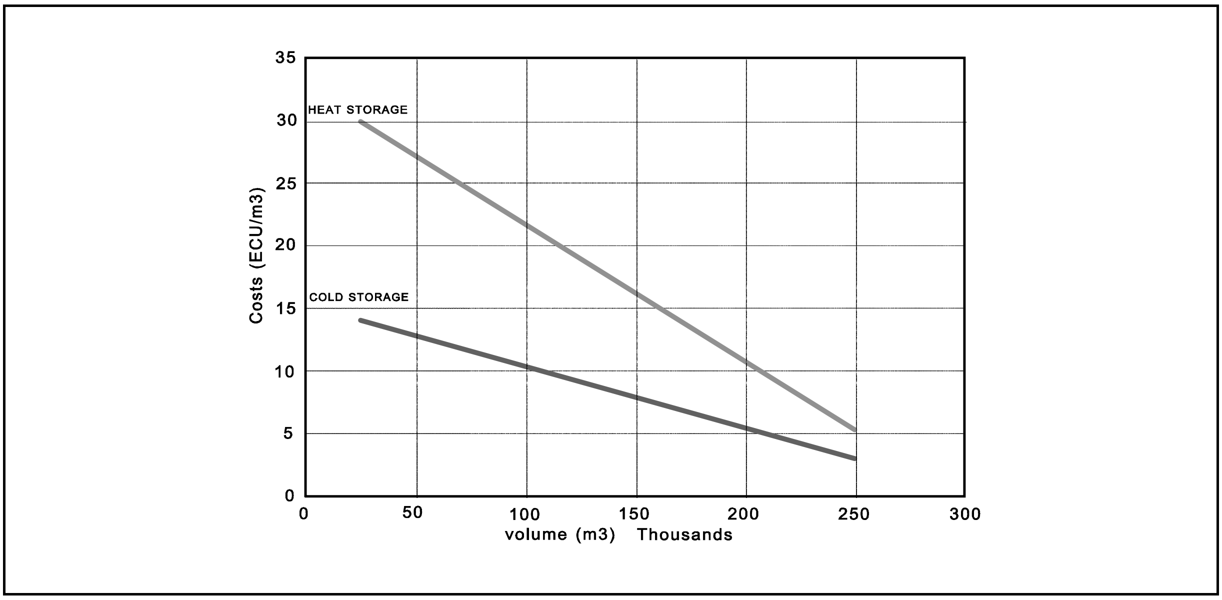

Figure 4.7 Specific investment costs for cold and heat storage against volume (Q =250 m^3/hour)

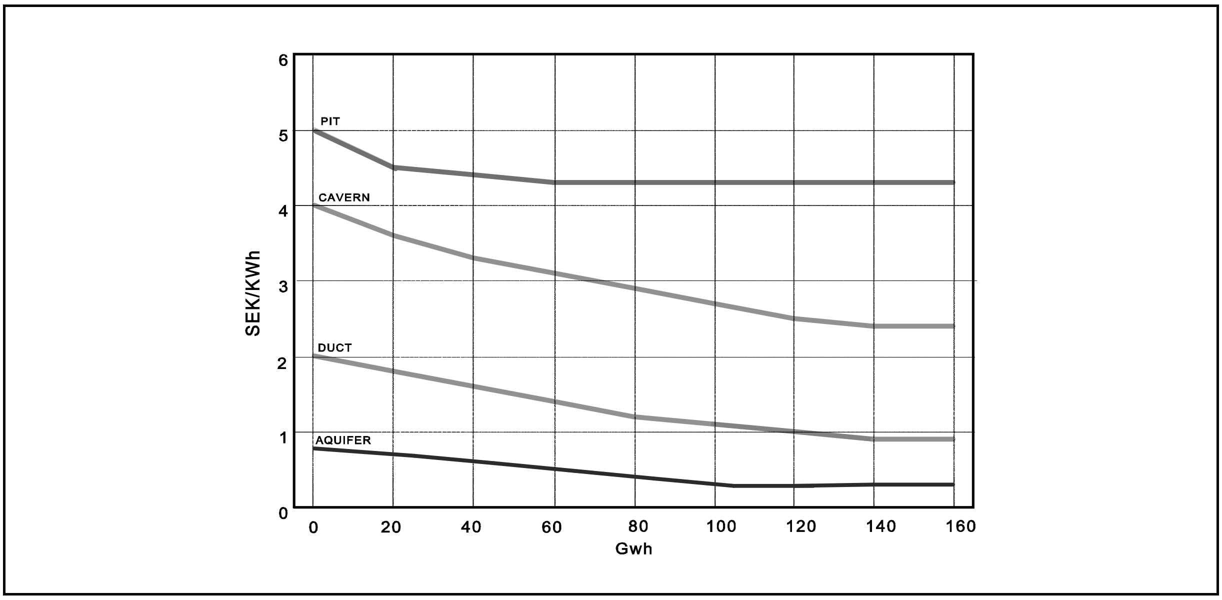

Figure 4.8 Specific storage costs for different storage techniques as a function of storage size

4.5 Cost comparison

As stated in the introduction, a cost comparison on the presented cost-analyses of the different storage techniques is hard to make. A major problem is the different ways of calculating costs.

To give a general impression of the costs relation between the different techniques, data from the Swedish Council for Building Research from 1990 are presented. The result of this data is a figure in which specific storage costs for heat storage are presented for different storage sizes (fig. 4.8).
As can be seen the techniques which use a natural storage structure are favourable in comparison to artificial structures. Aquifer storage is the most profitable. This can be explained by the fact that this technique makes only use of a few wells, while duct storage needs dozens of holes and while for cavern storage a tremendous amount of material has to be excavated

5. ECONOMY OF UTES

5.1 Economic approach to UTES

The profitability of UTES is determined by the additional investments and savings in operating costs. The final choice for a UTES will not only be determined by profitability. Particularly if the economic advantage of UTES is small, other aspects gain significance, such as operational security, space, environment, flexibility, and public relations. These "secondary aspects" will vary considerably between each application field and project.

In the sections below, an economic analysis will be made for each field of application (see Chapter 2). The conclusions from this exercise for the most part depend on energy prices, which vary per country and may in the future greatly deviate from the values used here.

5.2 Cold storage with and without heat pump

In Annex VII of the Implementing Agreement Energy Storage, "Innovative and Cost-effective Cold Storage Applications", much attention was paid to the economic and environmental aspects of cold storage and its alternatives. In that study, cold storage with and without heat pump was examined. Furthermore, a distinction was made between new buildings and renovation projects, and between aquifer storage and duct storage. The applications studied were space cooling and heating in the building sector, and process cooling in the industrial sector.

The study uses notional projects in four countries: Canada, Sweden, Germany, and The Netherlands. The energy system with storage is compared to an energy system in which cold (cooling unit) and heat (boiler) are generated separately: the "conventional system". Table 5.1 summarizes the comparison between conventional cooling and cooling with UTES for a new building. The systems with aquifer storage without heat pump have the lowest investment and operation costs, with as a result a negative S.P.T. (Simple Payback Time). Systems with heat pumps and duct storage are less attractive from the economic viewpoint. For industrial applications, cold storage is compared with cooling by means of cooling units (Table 5.2). To an even greater extent than in commercial buildings, cold storage is economically interesting. Savings on energy costs in industrial applications are in large part due to the large number of full load hours.

Table 5.1 Summary of Energy Cost comparison between conventional and alternative systems for new buildings.

Country	Canada			Sweden			Germany			The Netherlands	
System	convent.	only cooling	heat/ cool	convent.	heat/ cool	heat/ cool	convent.	heat/ cool	heat /cool	convent.	heat/ cool
Storage		ATES	ATES		ATES	Duct		Duct	ATES		ATES
Heatpump		No	Yes		No	Yes		Yes	Yes		No
System Characteristics ------------------------- Cooling demand (kW)	701	642	642	500	500	500	548	548	548	585	585
Heating demand (kW)	952	923	923	650	650	650	511	511	511	425	425
Annual cooling (MWh)	318	316	316	348	348	348	274	274	274	328	328
Annual heating (MWh)	705	694	694	1062	1062	1062	818	818	811	250	250
Cost (ECU x 1000) ------------------------- total capital cost total annual energy cost total annual cost S.P.T. (years)	 611 49 57 -	 598 45 52 negat.	 679 44 55 34	 1540 68 77 -	 1544 42 51	 1541 50 58	 1013 39 46 -	 1460 32 41 90	 1199 33 44 70	 417 36 47 -	 368 29 38 negat.

Annex VII also pays attention to the secondary aspects such as reliability, maintenance, space required, etc. of UTES. The problem with secondary aspects is that they cannot be generally quantified as can costs. (Table 5.3). Project specific circumstances will for a large part determine the value accounted to secondary aspects. Considering the relatively small differences between investment and operating costs for energy systems with and without cold(/heat) storage, in practice the secondary aspects prove to be very important in the final choice of a cooling system.

Table 5.2 Summary of Energy and Cost comparisons between conventional and alternative system for industrial process.

Country	Canada		The Netherlands	
System Storage HP	chillers	cooling ATES No	chillers	cooling ATES No
System Characteristics ---------------------- cooling demand (kW) Annual cooling (MWh) Cost (ECU x 1000) Total capital cost Total annual energy cost Total annual cost S.P.T. (years)	 600 5250 368 14 23 	 600 5250 364 8 14 neg.	 600 5250 519 43 59 -	 600 5250 608 12 31 3

Table 5.3 Comparison of chillers and aquifer storage (secondary aspects)

	Chillers	(Aquifer) storage
Reliability		
Technical reliability	- more sensitive to troubles	+ fewer moving parts, fewer breakdowns
Availability of cold	+ not applicable	- sensitive to climatic influences for load requirements
No-break power system	- relatively big system needed	+ small system needed
Repair time	0 comparable to storage	0 comparable to chillers
back-up capacity	0 comparable to storage	0 comparable to chillers
Maintenance and management	+ well known + one party involved	- unfamiliarity - extra party involved
Various aspects:		
Procedure or permitting	+ simple, short procedure	- more extensive procedure, more time needed
Starting period	+ not applicable	- should be taken into account for load requirement
Space requirement	+ no space required in the surroundings	+ smaller technical room required
General applicability	+ always applicable	- applicability depends on aquifer presence

5.3 Heat storage with solar collectors

Within the framework of Task 7 of the IEA Solar Heating and Cooling Programme "Central Solar Heating Plants with Seasonal Storage "CSHPSS", attention has been given to the economic feasibility. The economic analysis was done for the system configuration described in Table 5.4 These systems have been studied for four climate situations (Helsinki, Zurich, Milan and Madison) and for three project sizes {50 (800 MWh), 200 (3200 MWh), and 1000 (16000 MWh) houses}.

Table 5.4 Systems examined

main systems	collectors	storage
solar heating system	high temperature flat plate	pit cavern
solar assisted HP system	unglazed collectors	aquifer

The economics of solar heating systems is based on the annualized solar costs compared to the price of an available supplementary fuel 45 ECU/MWh (365 ECU/m^3 of oil, 80% efficiency) to assess the economics of solar heating systems in this analysis. This price can be considered to include some adjustments for pollution fees, etc. in those countries where actual prices are lower than this price. For the solar-assisted heat pump system, the same reference value has been used as for the solar system without heat pump.

The solar cost is the annualized capital cost of all the solar specific system components including collector array, the storage subsystem, the collector-to-storage transmission pipes, and the heat pump (if present). Operation and maintenance costs are included implicitly in the capital cost assumptions, but purchased heat (to meet 100% of the load) and power to drive water circulation pumps (in collector, storage and distribution subsystems) are not included. The economic life of the system is assumed to be 25 years and a real depreciation rate of 5% is used. This means however that if the system meets the criterion of 45 ECU/MWh the pay-back time is 25 years.

Figure 5.1 gives the solar cost as function of the solar fraction for a solar heating system in Milan. It is remarkable that the costs slightly increase with an increasing amount of solar energy. This can be explained by two tendencies:

- Decreasing efficiency of collectors with increasing collector temperature. The cost of the collector per unit of energy is an increasing function of the delivery temperature.
- Increasing efficiency of storage with increasing collector temperature. The cost of storage per unit of energy stored decreases with increase in the delivery temperature of the collectors. Therefore, there exists an optimum delivery temperature which minimizes the combined costs of the collector and storage subsystem The systems for 1000 houses have an optimum between 50 and 60% solar energy; the smaller systems lie below 50%.

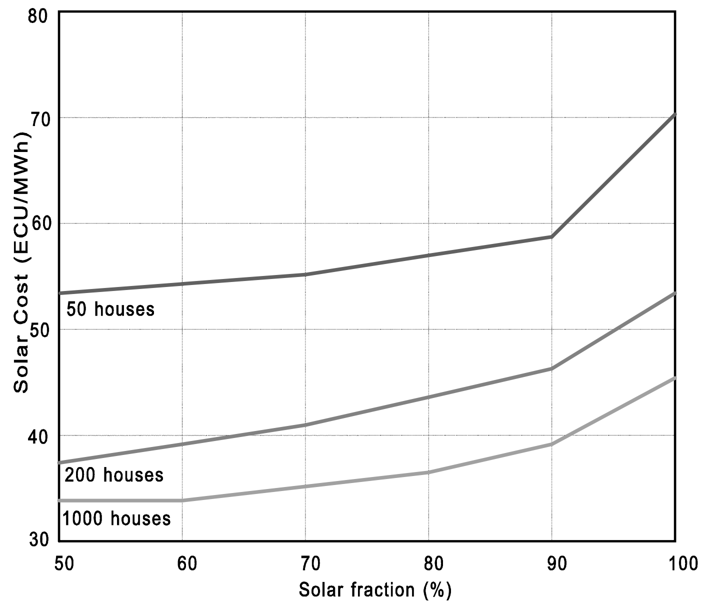

Figure 5.1 Solar cost for heating systems with ground storage for different load sizes in Milano

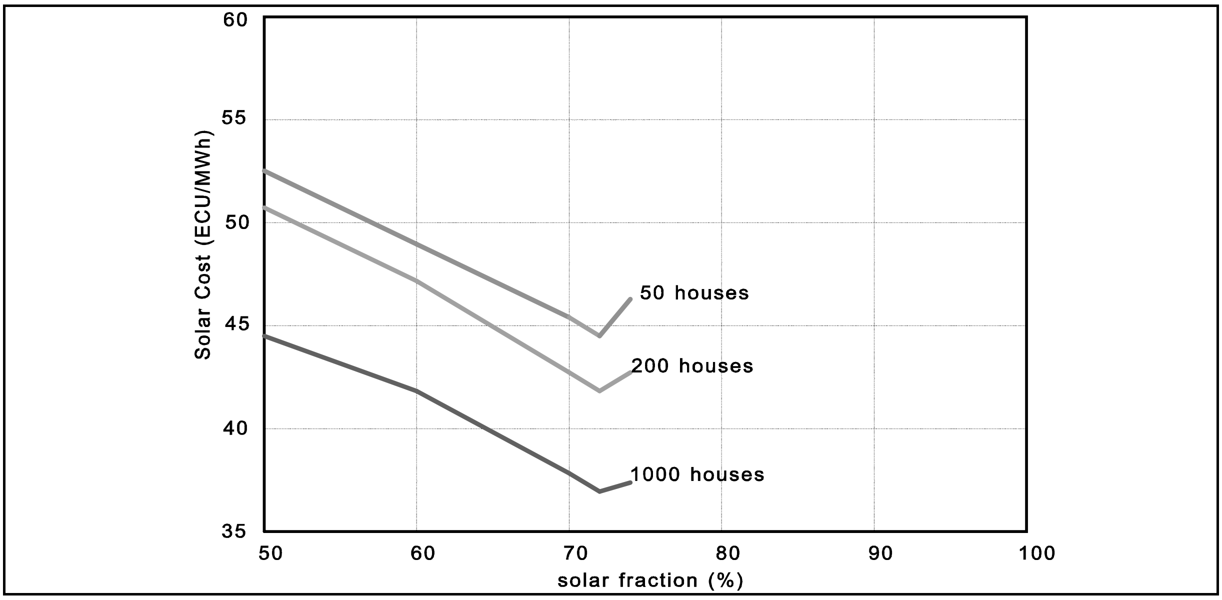

Figure 5.2 Total cost for solar assisted heat pump system with different load sizes in Helsinki

Generally the costs of solar heating systems lie between 37 and 72 ECU/MWh and therefore they satisfy the criterion of 45 ECU/MWh reasonably well. Solar costs are greatly influenced by climate. The systems in warmer countries can be up to 30% cheaper than in countries with a cooler climate. The way storage is done is of less significance as far as costs are concerned.

The functioning of solar-assisted heat pumps, which have been in use for some time now, is mainly determined by groundwater temperature. Given the fact that solar costs are lower than electricity costs, solar energy raises the system temperature to a level at which the heat pump becomes optimally functional. The solar fraction is about 70% in this case. An example of the solar cost curves for various project sizes is given in Figure 5.2

The most important secondary aspect for the use of solar collectors is space. For a system with a solar fraction of 70-80% and a heat demand between 3000 and 16000 MWh/year, the required collector area is 1.5-2.5 m^2/MWh.

5.4 Heat storage with heat/power units

The use of heat storage in combination with heat/power units has not yet been as systematically studied as the previous two applications. There have been studies in which this application has been included as an option. The small numbers and the varying reference situations used in those studies make it impossible to obtain unequivocal figures. Experience with heat storage at the State University of Utrecht indicate that a considerable energy saving is possible.

5.5 Heat storage in variable demand/supply systems

Research into the use of heat storage in these energy supply systems has not yet led to reliable figures with regard to their economic feasibility. At present, studies are being done in The Netherlands into a combination of heating for greenhouses and electricity generation.

From a Dutch study executed in 1992 into the combination of various types of energy users (housing, shops and offices) it is known that the possibilities for combined energy-saving are greater than for individual energy consumers. For heating/cooling and electricity, the integration of the different types make additional savings possible, respectively 20% and 10%.

5.6. Economy of realised UTES

The presented data in the previous sections were all based on notional projects. In this last section an attempt is made to give an indication of the economics of the realised projects. This analysis is made for some IEA countries.

The Netherlands

The Dutch experience is almost completely limited to aquifer cold storage. Cold storage in buildings is compared with cooling with chillers. Because of the high electricity consumption of the chillers and the high price of electricity: the economics for cold storage are favourable. This advantage will be even bigger when the coolants R11 and R12 are prohibited.
The realised project will be for 75% paid back within five years. There even are some projects with a less investment (negative pay-back time). Even if the pay-back time is more then five years, companies tend to choose cold storage. This is mainly caused by the secondary benefits. For industrial projects cold storage has to be compared with through-flow groundwater cooling. In 1995 a new tax on groundwater consumption of 0,17 guilder/m^3 has to be paid. Because energy storage is fully exempted from paying tax, economics for storage are also in favour of this application.

Canada

The use of energy storage in Canada is being accelerated by time of use rates and peak shaving incentives. Several electric utilities have adopted energy storage as one of the main elements of their peak load management program. The growth of storage has been principally for cooling in commercial buildings and ground and groundwater source heat pumps for combined heating and cooling in residential buildings.
Although Canadian buildings of all sizes are potential candidates for energy storage, present economically viable applications are focused on those cooled and/or heated with electricity. Thermal cool storage is now attractive in new commercial buildings and in many existing buildings given time or day rates and utility incentives for peak shaving. Ground and groundwater source heat pumps can be competitive when both heating and cooling are required, especially where natural gas is not available.

The simple payback of groundwater source energy storage technology is less than three to four years in most of Canada and least first cost applications have been installed. Present efforts to tap the latent heat pump ground moisture will greatly increase the efficiency of ground-coupled heat pumps. Integrated mechanical systems have been developed, some of which combine both ice and hot water storage for space heating and cooling. These systems have energy saving as well as peak reductions capabilities in single family house. It has been estimated that there are well over 10.000 existing buildings in Canada where the application of cool storage would reduce total investment and operating costs. This includes approximately 1800 large owner-occupied buildings which alone would result in peak demand savings of over 1000 MW(el). Assuming that only 15% of these buildings, over a period of three years, will have adequate technical and economic feasibility to install cold storage, the reduction in peak electric demand would be roughly 210 MW(el).

Process cooling sites in Canada range between 10.000 and 20.000, including at least 1600 food processing plants and 1000 ice surfaces. The potential for energy storage in process cooling is difficult to estimate, but should be large. Interest in thermal storage is increasing in Canada as more systems are being installed, more design and operating data is available, and more suppliers compete for jobs.

Germany

In Germany, the realized storage projects mainly use vertical earth heat exchangers (ducts). Thus no economic experience for aquifer storage exist. Studies for the Reichstag building in Berlin or for a sugar refinery in Anklam, show however good economics for aquifer storage in comparison with duct systems.

Duct systems exist for heat storage and for heat/cold storage. In the Donauwörth system with heat storage and solar collectors, the end-use heating energy did cost 0.248 DM/kWh; the cost for a conventional system would be 0.101 DM/KWh. A major part of the high cost for the system with storage is due to the diesel engine heat pump (0.14 DM/KWh), which was a kind of a prototype. The pure storage energy cost were 0.084 DM/kWh. Anyway, the overall system is not economic yet, but system improvements and simplifications (solar, HP) can help.

For heat storage, as when storing waste heat from cogeneration, economical advantages may arise under certain circumstances. Such systems may have a big potential in Germany. Though yet no plant of this type is operational in Germany, the economics could be good. A feasibility study on an 25.000 m^3 duct storage for such an application shows an energy price (storage part) of 0.08 DM/KWh

Four plants are equipped with cold storage, and economics, even for duct systems, is much better here. The sum of heating and cooling energy did cost between 0.058 and 0.144 DM/kWh, being about in the same range as the energy cost in a conventional system. In conclusion, when using ducts, the double use of the earth system for heating and cooling makes the plants economically viable or even favourable. A market growth can be expected for cold storage.

ATES also still has to show its merits in Germany. Good conditions for ATES prevail in the northern plains of Germany, in the Alpine Foreland, the Upper Rhine Graben and some river valleys. Nevertheless, a duct system is planned in good aquifer subsoil (sand) in Golm near Postdam. In process cooling cold storage systems could become economic easily in some of the German states, where a tax supplement on groundwater use for cooling purposes is imposed

(Berlin, Hessen). There is no practical experience with large storage plants for district heating in Germany, but the results of studies and R&D-projects encourage to proceed in this matter.

6 ENVIRONMENTAL ASPECTS OF UTES

6.1 General trends

The main positive environmental impact of UTES is energy saving. This is in the interest of sustainable application of energy sources and the reduction of CO_2 (greenhouse effect) and acid equivalents (acid rain). These environmental impacts are however mainly related to the environment compartment "air". To arrive at a balanced environment judgment of UTES, it is important to take other compartments, like water, ground, noise and space, into account. Besides one should also have to look at the environmental impact of the materials used for constructing and maintaining UTES. An life-cycle analysis of the used materials is however beyond the scope of this report.

6.2 Environmental compartments

- air

The actual reduction of emissions depends on how the energy is produced. Electricity is generated by various fuels. Table 6.1 illustrates this in an overview of the emissions per MWh_e for four countries. It shows that there is a considerable variation in the environmental benefit for electricity savings per country. The figures in Table 6.1 do not give any insight into the environmental impacts of non-fossil fuels such as nuclear energy and hydropower (waste, space requirements, etc.)

Table 6.1 CO_2, NO_x, and SO_2 emissions during electricity generation

Country	Netherlands	Sweden	Canada	Germany
Generation mix (%)				
coal	42.0		19.1	
oil	0.7		2.3	
gas	50.6		0.6	
non-fossil	6.7	90	78.0	35
fossil	93.3	10	22.0	65
Emission				
CO_2 (kg/MWh_e)	570	20.0	217.6	390
NO_x (kg/MWh_e)	1.08	0.1	0.6	0.4
SO_2 (kg/MWh_e)	0.87	0.5	0.7	0.5

For heating, despite the difference in fuels, the environmental benefit of energy saving for the various countries is less apparent (see Table 6.2).

Table 6.2 CO_2, NO_x and SO_2 emissions during heating

Country	Netherlands	Sweden	Canada	Germany
reference fuel	gas*	district heating	gas**	oil
CO_2(kg/MWh$_{th}$)	292	200	282	266
NO_x(kg/MWh$_{th}$)	0.2	1	2.7	0.2
SO_2(kg/MWh$_{th}$)	-	2	-	0.5

* 1 MWh = 146 m3 gas

** 1 MWh = 152 m3 gas

The emission tables indicate that from an environmental point of view it may be more attractive for one country to save electricity than for another, while another country in turn should give priority to economizing on heating.

For instance in a country where most of the energy is hydro-electrically produced, displacing electrical home and office buildings space heating and cooling with UTES technologies will have little impact on atmospheric emissions. However, displacing home or office building oil or gas burning furnaces with electrically driven heat pumps will have a significant impact on the environment. The electricity used by the heat pump, being hydraulically produced, is a cleaner source of energy than the thermal energy produced in the home or office by coal, gas or oil burning furnaces.
The displacement of conventional heating sources in a building with electrically driven heat pumps using UTES, results in an overall environmental impact in terms of atmospheric emission. If the COP of the heat pumps and UTES systems is greater than 1, the overall energy requirements are reduced (Strata Engineering Corp., 1992).

However in another country where the major source of electrical power generation is from combustion of fossil fuels, replacing an electrically heated and cooled building with UTES may have significantly positive impacts on the environment in terms of reducing atmospheric pollution, since the UTES is likely to consume less electricity to satisfy the heating and cooling demand.

Similar UTES projects can be considered more environmentally friendly in one country or part of a country than in another one. This is unfortunate considering that air quality ignores borders. UTES systems should therefore conserve primary energy independent of the way it is produced. Electricity should be used, as much as possible, for generating power and not for generating low temperature heating or cooling. For the latter, use should be made of sustainable energy in the form of renewable energy (outdoor air, solar, etc.) or of residual energy. The above will, however, only be possible when energy supply is looked at an international scale.

Besides the impact of CO_2, NO_x and SO_2, reduction in CFC-emission is important. The main detrimental environmental impact of CFC is damage to the ozone layer. CFC's are used in chillers and heat pumps. On average some 1-1.5% CFC leaks from those installations. In the studies mentioned in IEA the use of the cooling agent R-22 is assumed. Use of this agent will eventually be prohibited. Using heat pumps containing CFC's in UTES, a reduction of CO_2, NO_x and SO_2, causes a corresponding increase of CFC emission

- other environmental compartments.

In contrast with the compartment "air", other environmental compartments are only locally influenced. Because local circumstances can vary tremendously, making an unequivocal assessment of local environmental influences is unwise. The relationships between compartments can be very important, groundwater is given as an example.

Groundwater is commonly managed by local authorities. They have the duty to develop and maintain a sustainable groundwater system. When these authorities are confronted with a possible use of an aquifer for ATES, they have to balance the local influence on the aquifer with the supposed benefits to the atmosphere. In other words should allowance of a possible negative influence on the groundwater be made in favour of a positive influence on the atmosphere ?

The above example makes clear that when using an UTES the local environmental effects have to be critical examined. Local environmental effects need not be ignored in order to obtain an improved atmospheric environment. Indeed, acceptance and implementation of UTES will be encouraged by considering both local and global environmental effects.

7. EVALUATION

This report gives an up-to-date overview of the UTES technology. This evaluation attempts to summarize the report by some conclusions and recommendations.

Conclusions

* The last 15 years UTES has developed itself in a number of countries as a reliable, efficient and energy saving technique for generating and supplying cold and heat.

* The development level of UTES differs to a large extent between countries. In a number of countries UTES is applied on a commercial basis, while in other countries a strong call for pilot-projects exists.

* UTES has various applications; 80% of 60 realized projects in the "Annex 8" countries consists of cold/low heat storage. Approximately 50% of those projects is equipped with a heat pump. Heat storage in combination with solar accounts for the other 20%. In only one project heat storage with a heat/power unit has been used.

* The most prominent sector in which UTES has been used is the offices and services buildings sector. The prospects in agriculture and industry are also favourable although applications fall behind for those sectors

* Ducts and aquifers are the most frequently used storage techniques. Pits and caverns have been used in some place, but have less economical potential.

* Saving energy is the most important environmental advantage of UTES. The different way of generating heat and electricity makes that the reduction of CO_2, SO_2 and NO_x emission by UTES will vary strongly between countries.

Recommendations

* UTES can play a role in the search for a sustainable energy supply. How the term 'sustainable' is defined is significant in this regard. Often a reduction in emission, and not merely within national borders, is considered a sustainable characteristic of UTES. Sustainable energy in the form of use of renewable energy (outdoor air, sun, etc.) or of residual energy should be used whenever possible.

* In the past few years the main technical problems of UTES have been studied. Further study into certain fields and technologies is still required. However, the question remains whether it is desirable to solve the technical problems of economically less favourable techniques such as pits and gravel-water pits.

* UTES systems have in general not been adequately developed in commercial terms because of:

  - Incomplete integration of UTES and by not making full use of the possibilities UTES has within the energy supply system. As a result, the exploitation advantage is reduced and the pay-back period lengthened. The reasons for this are:
    - UTES is frequently not studied until the final design stages of an energy supply system;
    - in existing buildings the already present energy supply components are often an impediment to the optimal choice of an UTES.
    - building managers are generally not inclined to use UTES to cover their full energy requirement. Expensive back-up provisions are required.
  - Market conservatism. The market generally prefers 'proven' techniques. Furthermore, investors and financiers are strongly inclined to only consider the investment sum;
  - The low price of energy. A comparison between kWh prices of conventional and sustainable systems is generally unfavourable for the latter. However, a simple comparison of kWh prices is not justifiable. The current kWh price is an indication of costs for investments and fuels under present energy supply systems. The price does not, or hardly covers the social implications of such systems, such as the environmental damage caused. An environmental levy such as carbon tax on energy would perhaps alter the picture;

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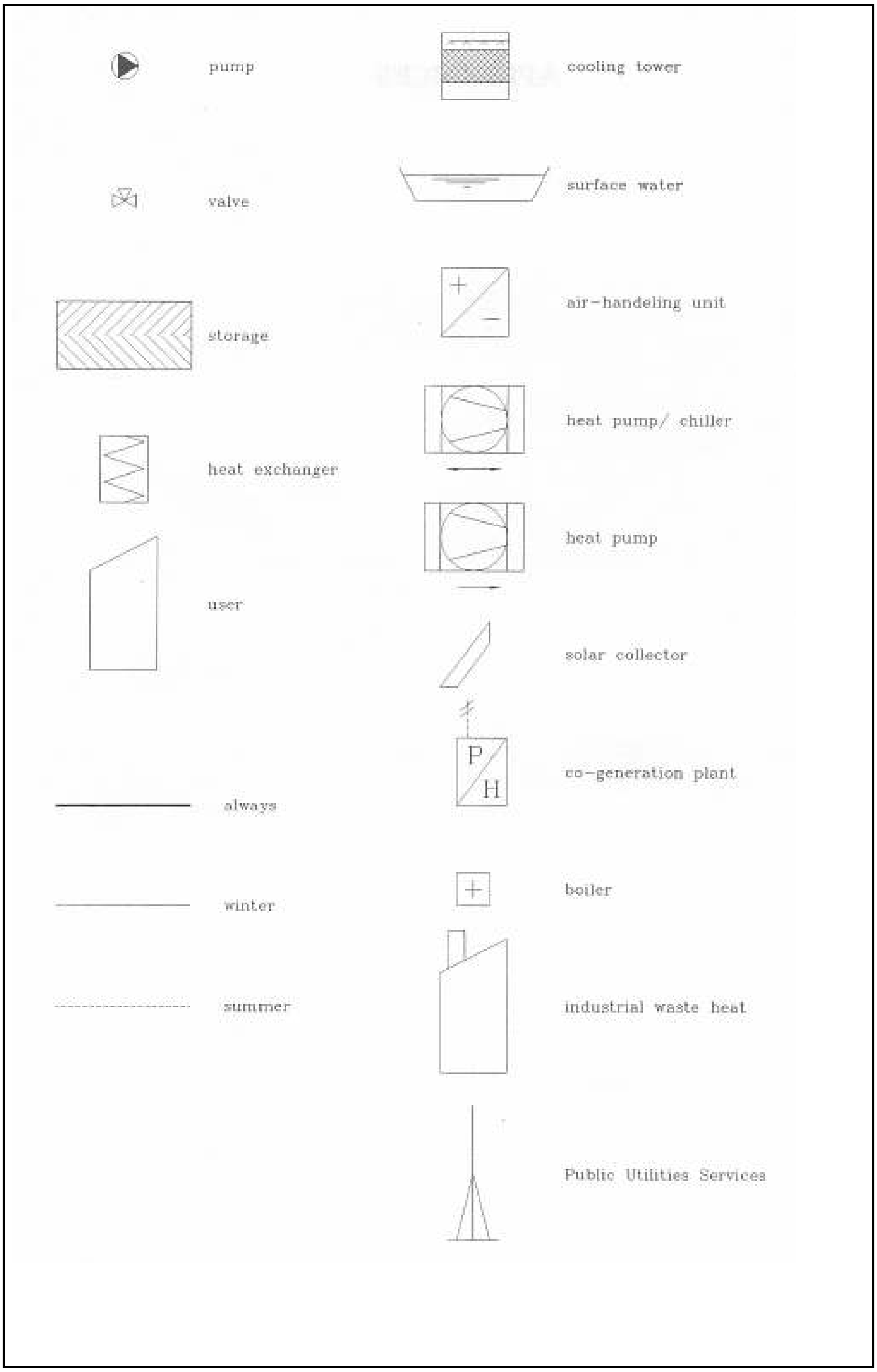
APPENDICES

APPENDIX 1 Legend system configuration drawings



APPENDIX 2a ATES at the state University of Utrecht, the Netherlands

1. General project description

There are 14 faculties at the State University of Utrecht including Veterinary Medicine, Physics, Law, Arts and Social Sciences. The 24000 students and 5000 staff work on two campuses: one in the city (110.000 m^2 building area) and one at "De Uithof" (335.000 m^2). The energy consumption at "De Uithof" is 37 GWh electricity and 10 million m^3 natural gas per year.

The heat required to heat the buildings of "De Uithof" is generated in two central plants and a number of satellite plants. In each central plant there are heat-power co-generation units. The electrical capacity of these co-generation units is 3.75 MW in the one plant and 4 MW in the other. Until now, heat demand dictated production. Excess electricity is sold to the Public Utilities Services.

In summer there is an excess of heat. By storing this heat and using it in winter for space heating, considerable savings on electricity can be made.
At "De Uithof", heat is stored in an aquifer, at a depth of 210-260 m below ground level. The principle of the system can be seen in the figure below.

In summer the aquifer is charged by withdrawing water from the relatively cold well, heating this water with the residual heat from the co-generation units and injecting it into the warm well at a temperature of some 90 °C. The warm water replaces the cold water and thus a warm bell is created around the warm well. When the heating season commences, the warm water is extracted and transfers its heat to the two buildings at "De Uithof" via a heat exchanger, after which it is injected into the cold well.

In the diagram below can be seen how the excess heat from the central plant for the Veterinary Medicine Faculty and from the central plant for the Mathematics and Physics Faculty is transferred via two heat exchangers and transported underground to load the aquifer.

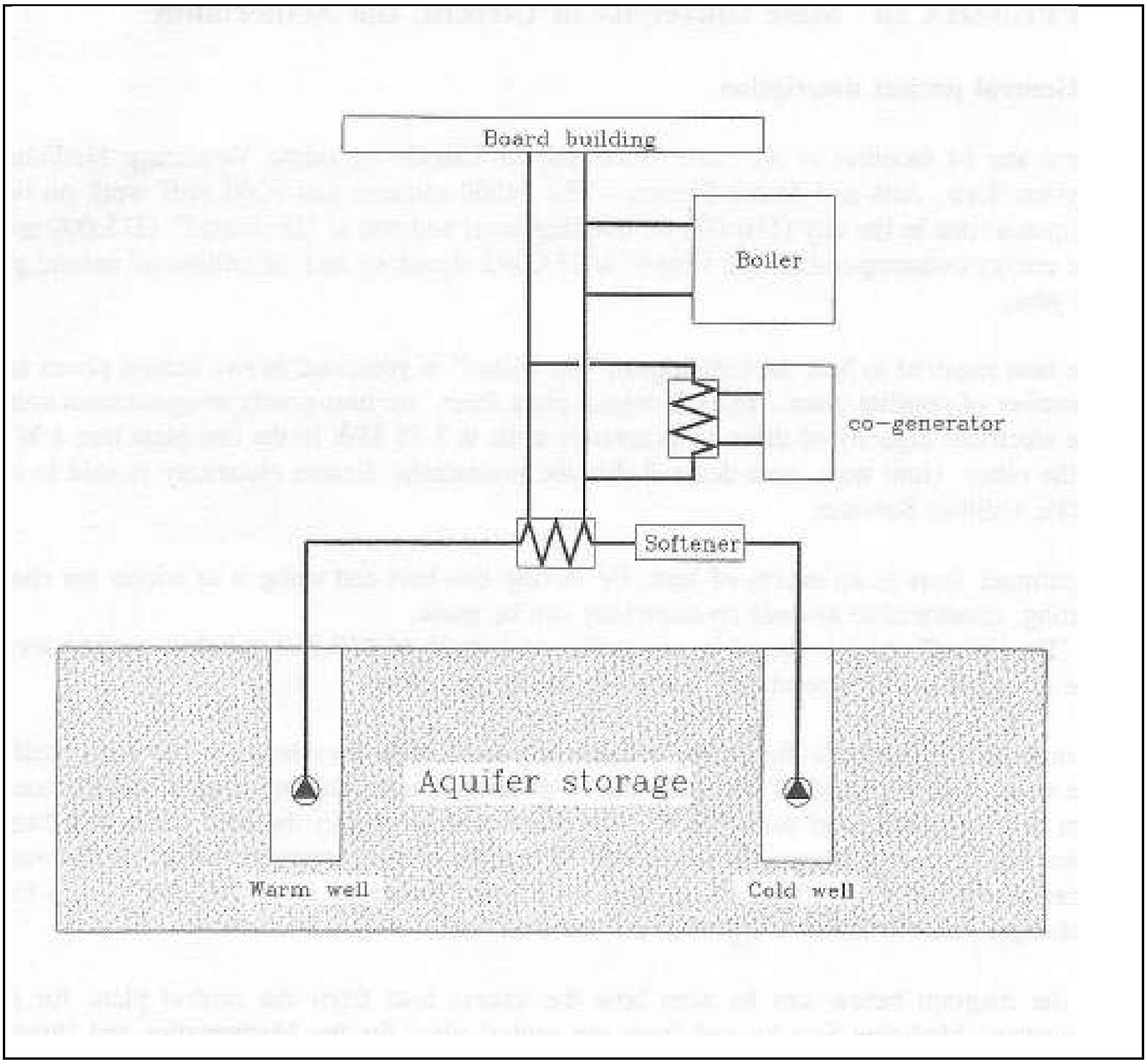


Figure 1 Simplified diagram of the principle of the system

During discharge, the return water from two buildings first passes the heat exchanger which is connected to the heat store, and subsequently it may be heated additionally by the boilers.

In order to prevent wells and heat exchangers being clogged by lime deposits, the groundwater is treated. For this purpose a water treatment unit (Ca/Na exchange) has been installed.

2. State of the Art (1994)

Table 1 Energy balance

years	loading GJ	unloading GJ	efficiency
1991	19.002	2.550	13,4
1992	9.557	3.610	37,8
1993	19.216	6.200	32,3
predicted	21.600	12.660	60,0

Due to lower energy amounts the efficiency is lower than predicted. Efficiency will be up to 60% in a balanced situation.

Water treatment is used only during loading. During treatment the water hardness is reduced to 6 DH. Due to that lower water hardness the amount of water to treated is reduced to 30% (first cycle 60%).

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APPENDIX 2b Heuvelgalerie, Eindhoven, The Netherlands

1. General project description

The "Heuvelgalerie" is to form a major feature in the town centre of Eindhoven. Its design provides for important functions such as shopping, a music centre, and catering services. An office block/congress centre, housing and a parking garage will complete the multi-functional centre. The predominant section as far as energy is concerned is the retail business with a gross shopping area of 24.000 m^2. At full climate control, a maximum heat discharge of 2400 kW in summer must be taken into account. The total annual heat surplus is estimated at 5000 MWh. The annual heat requirement for heating and ventilation is in the same order of magnitude.

The building complex is provided with heating and ventilation installations. Air conditioning is mainly applied in the shops and the music centre.
Heating is supplied by a central boiler that is connected to the various distribution networks via substations. The fuel source is natural gas. Air handling units supply treated outdoor air to the shops and malls as well as to the offices/congress centre. The music centre has a completely separate installation.

The thermal storage system has three components, which are in constant equilibrium. The above-ground system is an hydraulic entity and is separated from the underground system by a heat exchanger. The schematic principle of the whole is given in Figure 1.

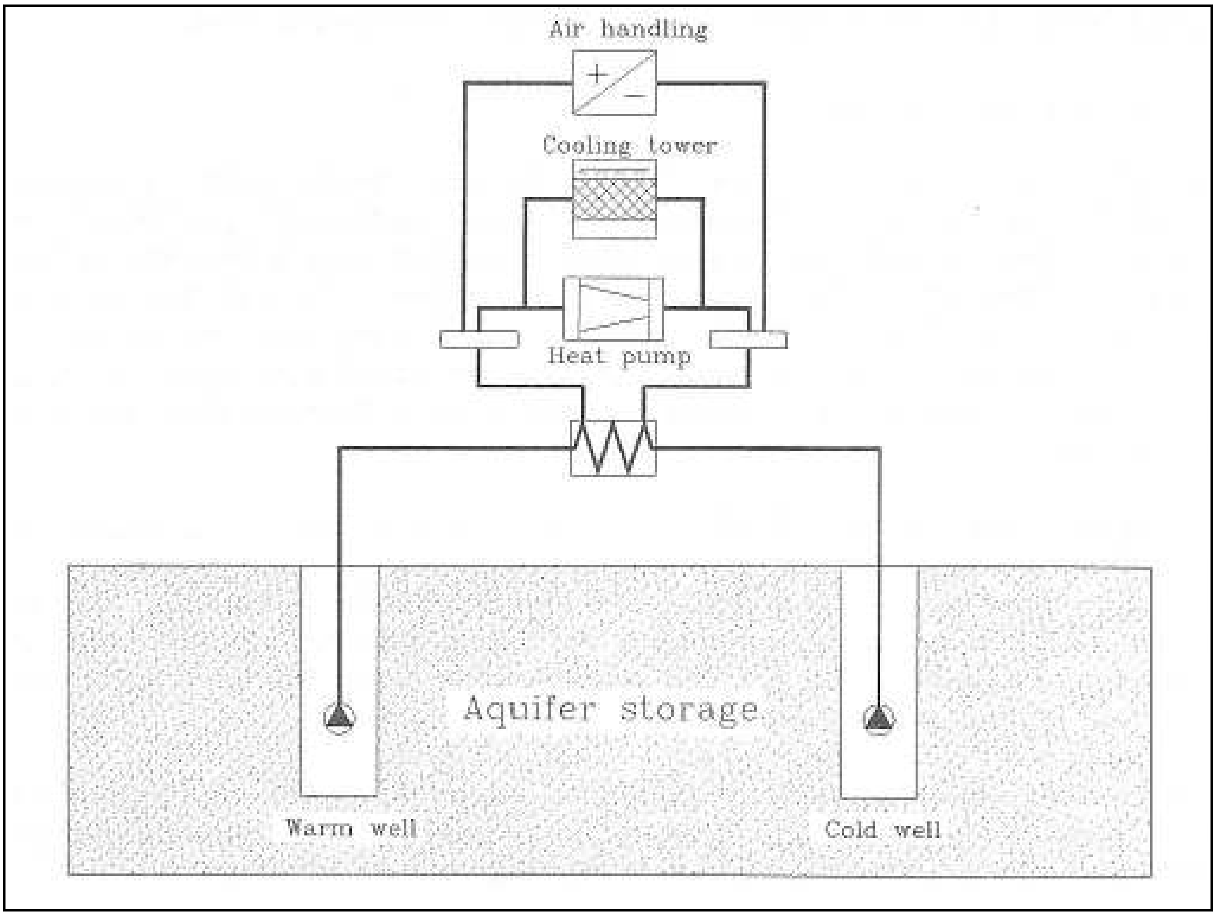

Figure 1 Principle outline

Ventilation system

At an outdoor temperature below 13°C the ventilation system requires heat. The total air displacement of approximately 215.000 m^3/h is divided over a number of units in the various sections of the building. At the design outdoor temperature of -10°C for winter, the required capacity is about 1700 kW.

Heat pump system

When shops are cooled, the heat pump system supplies heat at a water temperature of approximately 40°C. The maximum heat load is 2400 kW. Heat exchange between the heat pump units can take place within the system. Under extreme conditions extra heat van be obtained from the central heating system.
The projected cooling tower in the circuit can discharge excess heat directly into the atmosphere when maximum heat is supplied. This discharge possibility can also be used.

Storage in aquifer

The aquifer charges or discharges heat according to demand. If there is a heat surplus in the above-ground system, the excess heat is charged at the secondary end of the heat exchanger. Under design conditions heat is stored in the warm well at the desired injection temperature of

32°C. At a net head demand in the above-ground system, the warm well discharges heat and the water pumped up into the heat exchanger at the primary end will be cooled to the desired injection temperature for the cold well of about 18°C. The aquifer considered most suitable for thermal storage is found at a depth of 25 to 80 metres below ground level. This aquifer is highly productive and is suitable for groundwater extraction and injection at the required maximum of 100 m^3/h.

2. State of the art (1994)

In the summer of 1993 the system was used for cooling. Between May 1993 and November 1993 86.000 m^3 was stored at a temperature level of 30°C (1284 MWh). Only 2.400 m^3 (14 MWh) of stored heat was used during the winter because of the low temperature in the warm well.In the reference situation 3000 MWh will be loaded and 1500 MWh unloaded.

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APPENDIX 2c Jaarbeurs, Utrecht, The Netherlands

1. General project description

In October 1993, the Royal Netherlands Industries Fair in Utrecht opened the new multi-functional hall "De Prins van Oranje". This hall, measuring 85 metres wide, 185 metres long and 10 metres high, has room for a maximum of 25,000 people and as such is the largest events hall in the Benelux.

In the definitive design (Figure 1) loading is done by means of fans in each of the air handling units. Cold outside air is sucked in by the air cooler and subsequently discharged again. The cooling water is thus chilled in the air cooler and the cold is transferred to the groundwater circuit via the heat exchanger. Loading the cold is done at outdoor temperatures of +3 to -4°C, and takes place at times when the hall is not in use. At lower outside temperatures loading is stopped because of possible freezing. If the air-handling unit is operating to air condition the hall when outdoor temperatures are low (< -4°C) freezing is prevented by heating the coolers. The air coolers then function as pre-heaters in the air-handling units.
For hydraulic reasons the groundwater system is separated from the cooling water system by means of a heat exchanger. The flow direction in the groundwater circuit changes per season. To adjust the cooling water system flow to this, a fourvalve control has been included. To prevent air entering the groundwater system, it has been so designed that there is overpressure both during still-stand and operation. The main characteristic values for the groundwater system are summarized in Table 1.

A cost comparison between mechanical cooling and cold storage indicated that cold storage would be about Dfl. 300,000 cheaper. The costs for the complete cooling system, excepting the air supply system, was estimated at Dfl. 2.7 million at that stage. These costs excluded the additional costs for the engineering of the groundwater system and for the license application in view of the Groundwater Act.
The main positive environmental impact would be the electricity savings. In comparison to mechanical cooling, 60% electricity is saved. The savings on electricity costs are even higher (81%, Dfl. 30,000) due to a lower capacity rate.

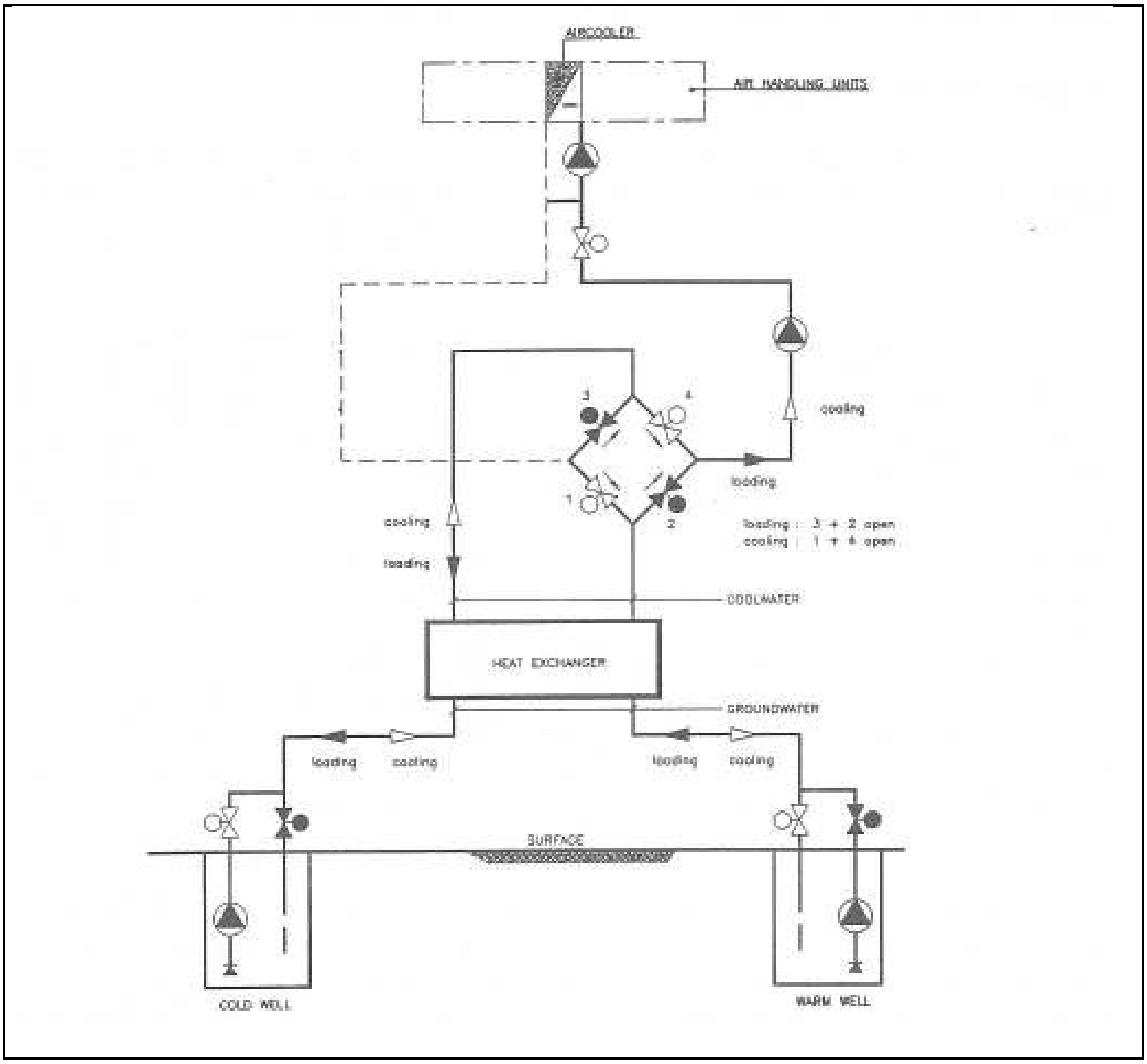

Figure 1 Design cooling system

Table 1 Characteristic values groundwater system

number of cold wells	2
number of warm wells	3
well diameter	0.8 m
screen setting wells (depth)	15-45
maximal summer flow	400 m^3/h
maximal winter flow	210 m^3/h
natural groundwater temperature	12.4°C
injection temperature winter	7°C
injection temperature summer	14°C
water displacement winter	75.000 m^3
water displacement summer	70.000 m^3
distance cold and warm wells	200 m
cooling capacity	2640 kW
cooling demand	400 MWh

2. State of the art (1994)

In the period up to 1 June 1994 a considerable amount of cold (162 MWh) has been loaded without significant disturbances.
Given the fact that in summer injection into the warm wells took place at an average temperature of 14°C, about 200 MWh is available for cooling in summer. This means that despite the very short loading period and the relatively mild winter, 50% of the required cold has been loaded.

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APPENDIX 2d Perscombinatie, Amsterdam, The Netherlands

1. General project description

In 1987, Perscombinatie N.V. modernized its press in Amsterdam by installing a new offset press. Because of the considerable heat released during the printing process the press hall needs to be cooled. In winter this can be done with outdoor air, but at temperatures above 11°C chillers are required to cool the air. With the utilization of the new printing press an extra chiller had to be purchased.

From a feasibility study it appeared that replacing this chiller by underground cold storage was technically and economically feasible.

The system was initialized in November 1987 by starting the loading program.

For cold storage in winter, groundwater is extracted from the "warm" well and after cooling injected into the "cold" well. The groundwater is cooled by means of a heat exchanger, which is installed in the cellar of the building. This heat exchanger is connected at the primary end to the groundwater pipes and at the secondary side to the building water cooling system. The heat taken up by the cooling water is transferred, via water coolers on the roof, to the (cold) outdoor air. In summer, the stored cold is transferred via the same heat exchanger to the existing water cooling system, which has then been connected to the secondary side of the heat exchanger via hydraulic switching. The heat exchanger then serves as a cool source which, parallel to the existing chiller is connected to the cooled water system. If there is a shortage of capacity, the chillers are used in addition to the heat exchanger as required. Experience and analysis of the measurements confirm the presumption that in "normal" winters the projected pay-back period will lie between 8.5 and 10.2 years, which is the principle for feasibility. Some technical data are listed in table 1.

As the winters were relative "warm" in comparison to the standard climate year applied in the feasibility study, the actual stored cold was in the period until 1992 considerably less than projected. That is why in 1992 the coolers in the air-handling units were replaced and the storage temperature was raised.

Table 1 Technical data

	before 1992	after 1992
maximum cooling capacity, total system	1650 kW	
cooling capacity provided by aquifer	550 kW	
annual consumption cold energy, total	1455 MWh(th)	
aquifer production after initial period	720 MWh(th)	1165 MWh(th)
pumping capacity per well	120 m^3/h	
volume of displaced water per season	200.000 m^3	
aquifer temperature (reference)	12 - 13.5°C	
warm well temperature	10°C	14°C
min. cold well temperature	5°C	9°C
max. cold well temperature	8°C	11°C
well depth	125 m	
aquifer depth	60 - 200 m	
screen depth	60 - 125 m	
distance between warm and cold well	75 m	

2. State of the art

In the winter of 1993/1994 loading was very successful 205.000 m^3 was stored with an average temperature of 8.2°C. Given the fact that in summer injection into the water wells took place at an average temperature of 13.5°C, about 920 MWh is available for cooling in summer.

3. Bibliography

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APPENDIX 2e Sussex Health Centre, Canada

1. General project description

The Sussex Health Centre is comprised of three buildings located in Sussex, New Brunswick, Canada. The buildings are a nursing home (3.000 m^2 floor area), a hospital (7.500 m^2 area-60 beds) and a Medical Centre (1.300 m^2 area). The complex is being adapted to Aquifer Thermal Energy Storage (ATES). The work is a joint venture of the, Sussex Health Centre, Environment Canada (EC), The Panel for Energy Research and Development (PERD), The Canadian Electrical Association (CEA), the New Brunswick Department of Environment (NBDOE) and the New Brunswick Power Commission (N.B. Power).

The Sussex Hospital which uses electricity as its only energy source, occupies a floor space of 7.500 m^2. An addition to the Hospital increased its size by 1.000 m^2, the addition is referred to as the Hospital Extension. The Nursing Home, which used #2 fuel oil for heating, has a floor area of 3.000 m^2. The 1.300 m^2 Medical Centre was commissioned in May 1994. The Medical Centre, which has zonal air conditioning, uses 21 water source heat pumps to transfer energy to and from the aquifer. Total energy consumption for the Hospital is 3.5 x 10^6 KWh. Of this amount, approximately 800.000 KWh is used for air preheat. It is this consumption that the ATES system will reduce during the heating season.

Annual life cycle cost savings of approximately \$ 86.000 are anticipated due to an energy consumption reduction of 1.100 of MWh and electrical demand saving of 450 KW.

There are two well fields, one cool and one warm, located on either side of the complex. In the first year of ATES operations groundwater is being transferred from the cool well field to the warm well field during the cooling season. It is intended to reverse this process during the heating season. Final temperatures for the cool and warm well fields are projected to be 6°C and 14°C, respectively.

2. State of the art

The Sussex Health Centre ATES system should be operational by July 1994. It will be monitored for a period of at least two years in order to determine the predicted energy and financial savings, and conditions in the subsurface environment.

It is expected that the success of this project will help to make ATES a standard design option in Canada by exposing buildings designers and engineers to the merits of ATES, and possibly other underground thermal storage (UTES) technologies.

3. Bibliography

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APPENDIX 2f ATES at SAS Frösundavik Office, Sweden

1. General project description

The head office of Scandinavian Airlines System, SAS, was completed in January 1988. The office building, with an area of 64 000 m^2, is heated and cooled by an energy system, which uses the underlying aquifer as an energy storage both for short time storage and seasonal storage.

The heating demand is approximately 3 MW, including heating of ventilation air and hot water demand. The annual energy demand for heating is about 3 GWh, excluding additional electric heaters in some office rooms. The cooling demand has been about 0.7 MW, but is designed for a higher demand (approx 2 MW) to include a building with a central computer. The yearly demand is about 3 GWh which is of the same order as the heating demand.

The energy system is based on five wells which are used both for injection and withdrawal. Three deep wells (approx 25 m deep) are located in the centre of the storage for storing cold water, down to 2°C. Two shallow wells (approx 10 m deep) are used for storage of warm water. One of the warm wells is located 250 m north of the cold wells and the other is located 100 m south of the cold wells. The total volume of the aquifer is about 1.5 million m^3. The aquifer storage volume is about 800 000 m^3, which can be charged by actual well configuration. Installed pump capacity is 0.190 m^3/s.

Heat is produced by extraction of "warm" water (approximately 15°C) from two wells. Pre-heating of incoming air for ventilation is made by direct heat exchange with the warm ground water. The demand of tap water and of supplementary heating of incoming air is ful-filled by three heat pumps. The chilled water, which has a temperature of approximately 5-8°C, is injected into the cold wells during periods with heat production. The building is cooled by groundwater from three cold wells. The cooling is distributed by cooling panels in the office rooms and by cooling of the incoming warm air.

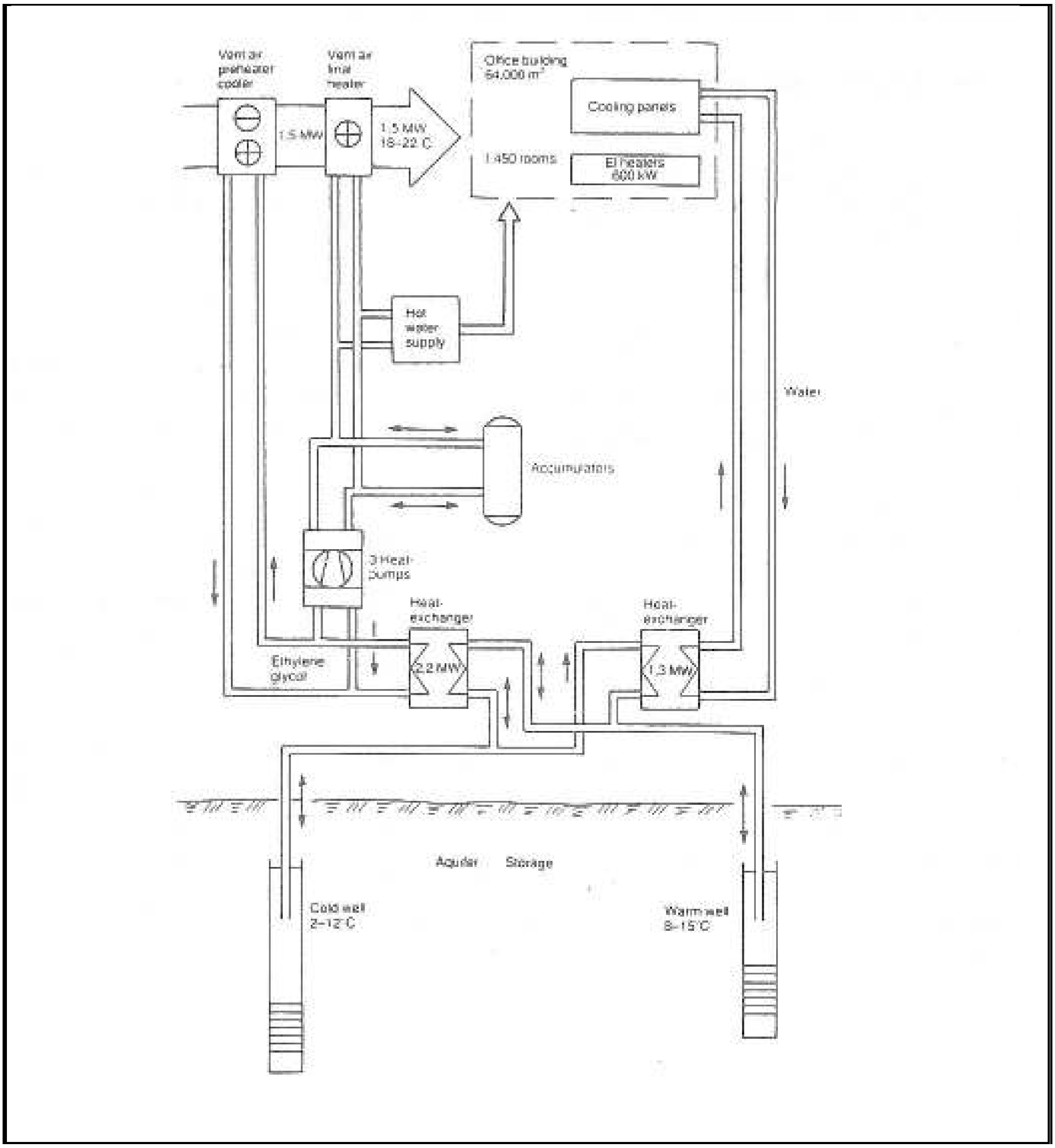

Figure 1 Principle flow sheet for heating and cooling system

2. State of the art

Experience from six years operations shows that the energy system has fulfilled design expectations. The yearly heat production is about 3.5 GWh, and the production of energy for cooling is about 2.8 GWh. For this energy production, average 6.3 GWh (both heating and cooling), the energy system has consumed 1.17 GWh electrical energy, which gives a system COP of 5.4.

Table 1 **Energy production from the ATES at SAS Frösundavik. Data for the first year, 1988, is unfortunately not available.**

Year	Heat production (MWh)	Cold production (MWh)	Electricity consumption (MWh)	System COP
1989	3521	3150	1221	5.46
1990	3412	2964	1021	6.25
1991	3425	3070	1242	5.23
1992	3069	2494	1116	4.98
1993	4153	2297	1239	5.21
Average	3514	2795	1168	5.40

The system has shown a high performance. Almost no problems with ground water chemistry have occurred in the circulated water (one well was cleaned twice in 1988). The energy system has been operated since the start in 1988 by employees at SAS. A special training course was held in April 1990 and since July 1990, SAS is also responsible for all measurements, operation strategies and optimization of the operation.

The annual saving is about 0.7 MSEK compared with a conventional energy system. The investment cost for the aquifer energy system was estimated to be about 3-4 MSEK, giving a Pay-Off-Time of about 5 years.

The total cost for energy production (heating and cooling) is 0.43 SEK/kWh, including operation, maintenance, personnel and financial costs. The corresponding cost for a traditional system with district heating and cooling machines is 0.55 SEK/kWh.

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APPENDIX 2g The "Sparven" telestation ATES Plant, Sweden

1. General project description

"Sparven" is the name of a telecommunication building located in the city of Malmö, southern Sweden.There are three individual buildings with a total floor area of approximately 27 000 m^2. The buildings vary both in age and in sophistication of the telecommunication equipment.The buildings are heated by the local district heating network.

In 1985 a central cooling system was constructed to supply the cooling need for new electronic equipment and to replace older individual chilling systems. Two chillers were installed, one for summer use (500 kW) and the other one to be used during the winter. The latter one is a combined chiller/heatpump (300/300 kW) for both cooling and heat recovery. Offices and some other localities have different forms of air ventilation, some with recirculation, some with fresh air inlets only, and some with common air suction. In total there are ten individual fan-rooms in the buildings.

In 1987 an emergency cooling system based on groundwater was constructed. The groundwater is extracted from three wells in the frontcourt of the buildings. The water was initially dumped into the city sewage system.

In 1989 plans were made to use the groundwater as the prime cooling system and to keep the chillers as back-up. The concept consisted of an ATES system with two sets of wells, one group for production and one for reinjection. It was designed for both cooling and heating as shown in the figure below and constructed 1990/1991. However, the air-conditioning part has not yet been fully built.

At present, the cooling demand is in the order of 300-400 kW but it has been designed for 800 kW. The maximum groundwater flow is 150 m^3/h. While waiting for the air conditioning system to be fully constructed, rechilling of water is done by using existing roof condensers.

2. State of the art

The main objectives for the construction were:

- economically profitable
- less noise
- better cooling security
- less fluor-chlor-methane handling
- better drainage of the buildings
- better internal environment

Economically the system should be running nearly continuously to meet the design profit. This means a technical operational time in the order of 8000 hours per year. Due to strategic operation of the chillers, the running hours have been considerable lower and therefore this goal has not been fully achieved. Still, it is judged acceptable.

From an environmental point of view there has been an approval regarding the internal noise, and in addition, since the chillers are in operation, less CFC handling has been decreased. The groundwater system will also allow a shut-down of the chillers for conversion to an more environmentally approved cooling medium (R134a planned).

The extraordinary mild winters the first two years of operation led to less recooling of the water than expected. As a consequence, the aquifer has been slightly warmed up and hence the production temperature has increased by approximately 1°C. However, over the winter 1993-1994, maximum recooling has been achieved, and the aquifer temperature is expected to drop again to design values.

Recently a second plant has been constructed and taken into operation in the vicinity (March 1994). This plant is designed to inject cold water very close to the production wells at "Sparven". The reason for this is to help keep the production temperature at "Sparven" at a low level.

3. Bibliography

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APPENDIX 2h The Lomma ATES Plant, Sweden

1. General project description

Lomma is a small village some ten kilometres north of Malmö, southern Sweden. The major part of the village is connected to a district heating system rated for roughly 20 MW peak power at a maximum temperature of 90°C. The main portion (60 %) of the energy is produced with a heat pump system. All together the output power is 4.300 kW split into four heat-pump units, almost equal in size. As a source of energy to the heat pump system surface water from a nearby river (Höje å) is used either directly or from an aquifer storage. The surface water is pumped from the river to the central heating unit, where energy is extracted through two heat-exchangers.
One heat-exchanger, HEX 3, is secondarily connected to the evaporator brine circuit of the heatpumps, while the other (HEX 2) is connected to the groundwater circuit. The maximum surface water flowrate is in the order of 800 m^3/h while the groundwater flow is rated at 300 m^3/h or 60 m^3/h.

In summer there is an excess of heat in the surface water. This energy is stored in the aquifer using five warm injection wells at a mean temperature of 14°C. In winter, when the river has a temperature lower than 5°C, the stored energy is recovered by pumping the warm wells the energy is transformed by the heatpump circuit and a third heat-exchanger (HEX 1). During spring and autumn the river is used as a prime source of energy while the aquifer system is used for support or back-up. The aquifer system is designed for storage and recovery of approx 10 000 MWh/year. It was put into operation in early 1991.

2. State of the art (1993)

The functioning of the system has been closely monitored from May 1991 to April 1993. The main conclusions from this monitoring period are as follows.

The heatpump system provided 60-65 % (22-24 GWh) of the heat demand which was a little better than expected. As a source of energy to the heatpumps the aquifer provided 8-9 GWh while the surface water directly delivered 5-6 GWh.

Less energy than predicted was stored in the aquifer despite two warm summers. The main reason for this has been problems with biofouling of the heat-exchangers. However, cleaning increased the efficiency of the exchangers from roughly 2000 MWh stored in 1991 to some 6000 MWh in 1992.
For the time being (May 1993) there is a negative balance of roughly 8000 MWh in the aquifer causing increased "cold bubbles" around the cold wells.

Due to the problems with biofouling and hence less effective heat-exchanging between the surface-water and the groundwater, the mean storage and recovery temperatures became slightly less then calculated. However, the mean storage temperature improved from 12,5 to 14°C the second year and the mean recovery temperature from 10,5 to 12°C.
By continued improvements in the cleaning of the heat-exchangers combined with an increased usage of the river water as a direct source of energy to the heatpumps the negative energy balance of the aquifer will be restored in a few years.

3. Bibliography

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APPENDIX 2i Borehole Heat Store at GLG-Center, Sweden

1. General project description

The GLG-Center project is situated in a modern office building, 40 km north of Stockholm. The building, with an area of 110000 m^2, is heated and cooled by a system which includes a borehole store in rock. The system has been in operation since 1989. The total cooling capacity is 3000 kW from which 480 kW is related to cold storage.

System concept
The 110,000 m^3 store consists of 64 vertical holes; spacing=4 m, diameter=115 mm and depth=110 m. A heat pump connected to a closed single U-pipe system is used for heat injection and extraction. A floor heating/cooling system, TermoDeck, is used. TermoDeck is also a day storage system.

Modes of operation
Summer mode
In the summer the cooling machines produce waste heat which is stored in the heat store, i.e. cold is extracted from the store, by a warm brine circulating in the pipe system. The TermoDeck, which is part of the ventilating system is cooled.

Winter mode
During the winter, when the heating demand is greater than the cooling demand, heat is extracted form the store and, the store is charged with cold.

Economy
The seasonal cold storage implied an extra cost of investment of 3500 kSEK including subsidies from the BFR. The pay-back-time was calculated at 8.5 years.

Experiences from a realized project
No major problems. The store is a reliable part of the heating/cooling system.

2. State of the art

There is a great number of Swedish borehole heat stores similar to that at the GLG-center, with a heat pump for heating and cooling purposes.

3. Bibliography

Nordell B. 1991, GLG Heating/Cooling Storage System. Proc. of IEA Workshop on Generic Configurations of Seasonal Cold Storage Applications. Utrecht, The Netherlands, Sep 18-19, 1991.

APPENDIX 2j Technorama Düsseldorf, Germany

1. General project description

The Technorama building is of the "passive solar" type. Transparent insulation of the outer shell and the roof of a large atrium (sunspace) provides substantial solar gains. Hence annual heating load is reduced, but cooling of office rooms and laboratories is essential during summertime in addition to shading. Computer facilities also need to be cooled most time of the year.
The ground is sand and gravel of Tertiary age, with substantial groundwater movement. The store consists of 77 earth probes, grouped in 4 clusters with individual manifold for each group. The earth probes are steel tubes, diameter 40 mm, rammed into the ground by pile driving equipment. In each cluster, the steel tubes have been arranged radially with a dip angle of 45°. The earth probes are of the coaxial type, brine flows down through a plastic pipe inside the steel tube and comes back through the annulus between plastic pipe and steel tube.
Six heat pumps are working in parallel, all connected to the same manifold on the "earth side" and to the same buffer tank on the "building side". To meet lower heat demand in spring and fall (and on sunny days in winter), only a part of the heat pumps is used. Computerized energy management in the building ensures adaption to the actual heating-/cooling-requirements.

Figure 1 shows the plant. In winter, heat pumps heat the building and cool down the ground. In the begin of summer and on days with small cooling demand, brine is circulated through heat exchangers, transferring cold to the building's cooling system. To reduce the number of mixing-/shunting valves, the brine has to pass through the heat pump evaporators before reaching the heat exchangers. On hot days and in the end of the cooling season, when cold in the ground has been exhausted, the heat pump working direction is reversed and heat is transferred from the buildings to the ground store.

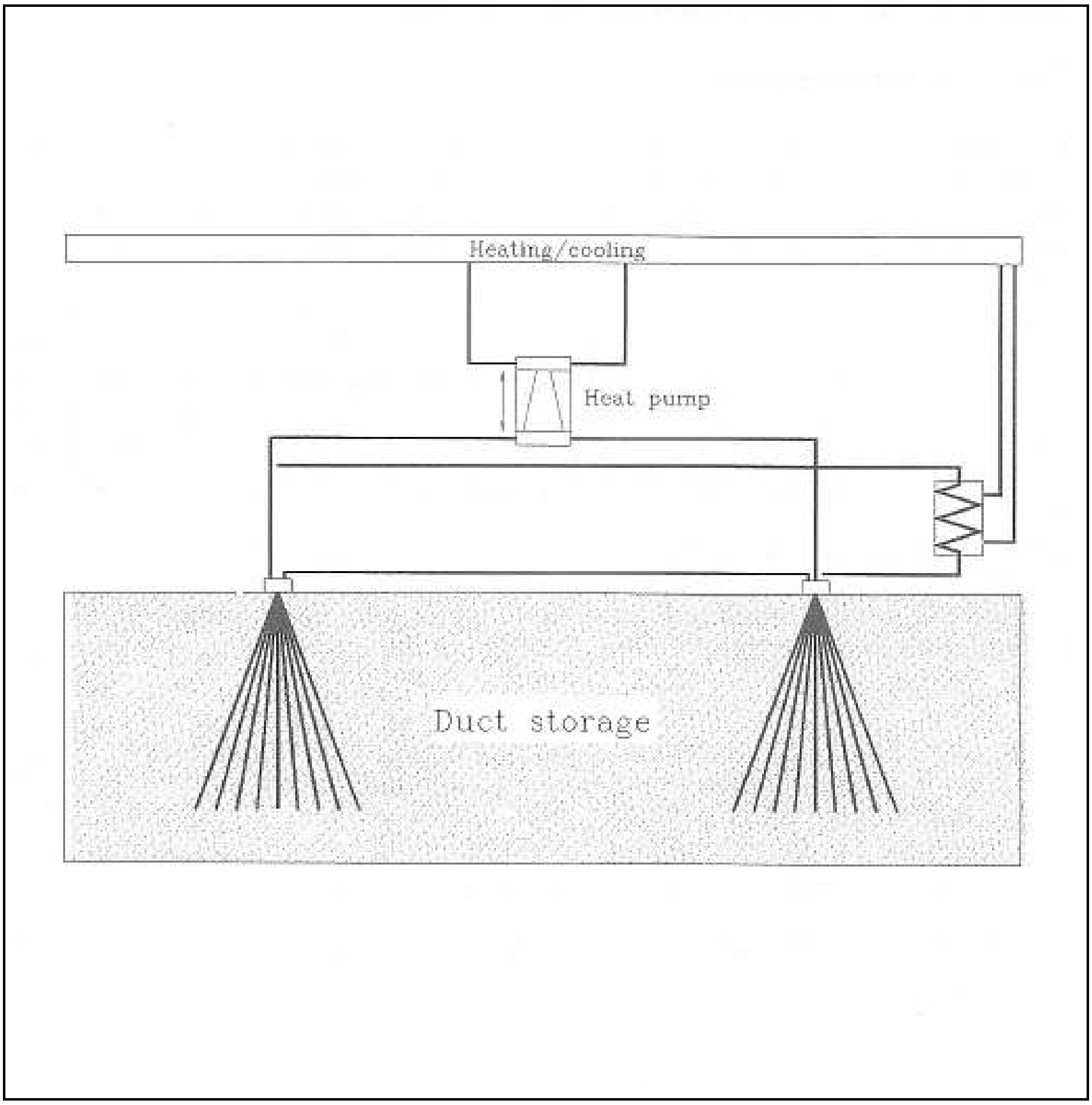

Figure 1 Flow sheet principle of the system

2. State of the art

The plant is operational since November 1990. The monitoring system in Technorama Düsseldorf caused a lot of problems. First measurements of energy flows and of fluid temperatures in the system have not been consistent. A new inductive flowmeter had to be installed for the earth circuit. Temperatures in the stores can be measured since Oct. 1993.

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APPENDIX 2k Project Donauwörth, Germany

1.General project description

The installation is located in the south of Germany (Bavaria) near Donauwörth. The system consists of a solar collector, duct storage and heatpump for space hating of a two-family-house and an office building with workshop. The total heat demand of both buildings is 60 kW with an average yearly energy consumption of 110 MWh/a.

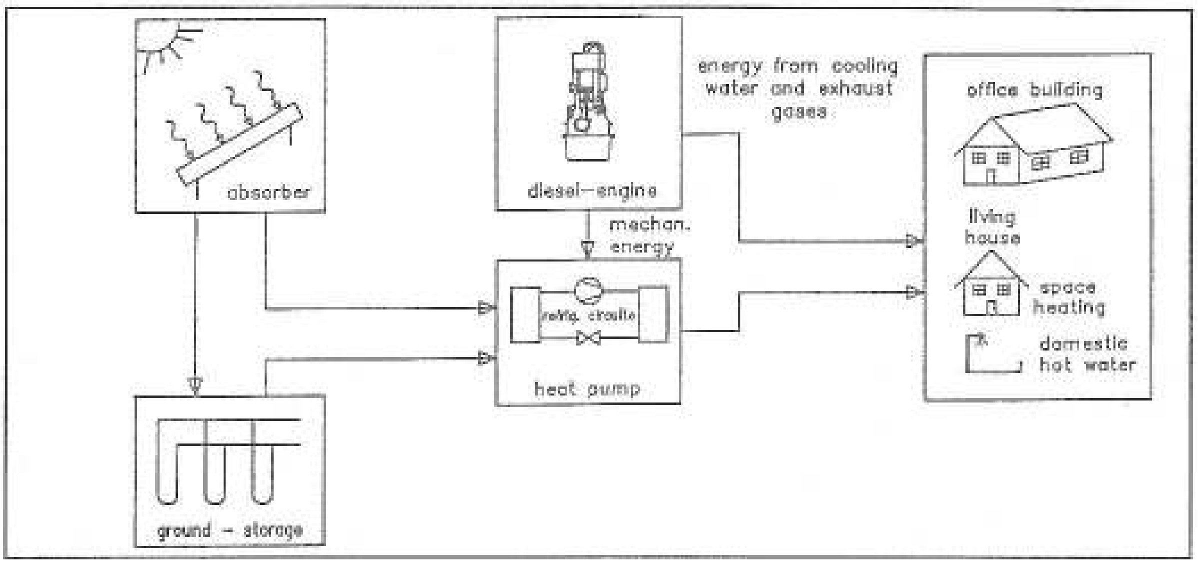

Figure 1 Scheme of the plant

The unglazed solar collector has a total area of 100 m^2. This type of collector is commonly used for low temperature applications like swimming pool heating and favourable for its effectiveness and low price.

The ground storage has an overall volume of about 3.000 m^3 consisting of 104 boreholes of 150 mm diameter with an average length of 10.5 m. In each borehole one U-shaped polypropylene heat exchanger is inserted, the hole is refilled with a special mixture of bentonite, cement, sand and water to gain the thermal contact to the soil. The storage characteristics are summarized in table 1.

The ground storage is designed to be heated up to temperatures around 25-30°C at the end of the summer (charging period)

A diesel-engine heatpump is used to extract the energy from the storage and to increase the temperature level of the heating fluid to 45-55°C, which is required by the heating system of the buildings. The engine is directly connected to the multicell rotary compressor of the refrigerant. The whole plant is controlled by a free programmable microprocessor based control unit.

Table 1 Characteristics of the ground storage

Soil properties			
type of soil: (10 m depth)	loam, 15-20% clay, fine-medium sand	water content (per weight):	21%
		porosity (per vol.):	37.8 %
bulk density:	1.7 g/cm^3	therm. conductivity:	1.1 W/mK
therm. capacity:	1.66 kJ/kg K		

Heat exchangers			
boreholes:	104	diameter:	150 mm
depth:	10.5 m	distance:	1.6 m
backfill material:	bentonite, cement, sand, water	av. thermal conductivity: of backfill material:	1.0 W/mK

2. State of the art

The system can be operated in three different modes:

- charging of the ground storage
- discharging of the ground storage
- combination of discharging of the storage and direct solar.

In summer solar energy is used for charging the ground storage (1st mode). The second mode is typical for winter operation, energy is extracted from the ground storage by the heat pump and used for space heating. On sunny days in winter and spring the heat pump, depending on the temperature level, is either using the storage or the collector as heat source.
The total system costs were 83.350,- ECU of which the collector needs 7.085,- ECU, the heatpump 46.090,- ECU and the ground storage 30.175,- ECU. The annual costs amount to 750,- ECU for maintenance and 1.785,- ECU for diesel fuel.

The specific energy costs for the solar energy delivered from the collector are 0.012 ECU/kWh, for the storage 0.042 ECU/kWh and for the heatpump 0.070 ECU/kWh, in total 0.124 ECU/kWh useful heating energy. In comparison the specific energy costs for a conventional oil based heating system amount to 0.051 ECU/kWh. By standardization of components and techniques there is still a potential of cost reduction.

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