OPEN-LOOP GEOTHERMAL HEAT PUMP SYSTEMS IN THE USA AND AQUIFER COLD STORAGE IN THE NETHERLANDS - SIMILARITIES AND DIFFERENCES

Guus Willemsen

IF Technology
P.O. Box 605
6800 AP Arnhem, The Netherlands
Tel.:+31 26 4431541
Fax:+31 26 4460153

ABSTRACT

Aquifer cold-energy storage is based on the use of groundwater to store winter cold for later utilization in summer. A related technique with geothermal heat pumps also extracts thermal energy from the soil and injects it into the underground. The latter is not operated with the intention to recover the stored energy later, but only to use the soil to extract and discharge thermal energy. Two methods are available to connect heat pumps to the soil: a closed-loop and an open-loop system. With the open-loop system groundwater is extracted and injected later, as is done with cold storage. This paper has been drafted to compare the open-loop and cold storage techniques as regards their energy systems, groundwater use and economy. The main conclusion is that a combination of cold storage with heating by means of heat pumps will always result in higher energy savings than an open-loop geothermal system only. Also from the technical and economic points of view, such a combination seems to be feasible and attractive.

1. INTRODUCTION

Recent publications (Bakema & Snijders, 1998; Willemsen et al., 1994) have shown a rapid increase in the number of cold storage projects in the Netherlands. The cold storage principle means that groundwater is extracted from "warm" wells in winter, chilled with outside air and - at some distance from the extraction well - re-injected into the soil through the "cold" well. In summer the same water is extracted from the "cold" well, used for cooling while absorbing superfluous heat and subsequently re-injected into the "warm" well.

Parallel with this development there is another, yet similar, development taking place in the USA. There, heat pumps are connected to soil heat exchangers (closed-loop system) or to groundwater systems (open-loop system). These heat pumps supply cooling in summer and heating in winter. Especially the open-loop systems show remarkable similarities with cold storage. In both cases groundwater is pumped from the aquifer, heated or chilled, and re-injected into a well at some distance. Bakema & Snijders (1998) outline the differences between the two systems. The present paper is an attempt to study more profoundly the similarities and differences between the two principles, as regards energy system, groundwater use and economy.

2. ENERGY SYSTEMS

2.1 Similarities

The two energy systems have the following in common:

- extraction and re-injection of groundwater.
- utilization of this groundwater at least for cooling and in most cases also for heating, especially for interior space conditioning.

2.2 Differences

Projects reported by the Geothermal Heat Pump Consortium (GHPC) have been compared with projects in the Netherlands (Bakema & Snijders, 1998; Willemsen et al., 1994). The size of the average open-loop geothermal heat pump system in the USA appears to be relatively small compared with the average cold-storage project in the Netherlands. This is due to the fact that in the USA there is much more emphasis on the cooling of houses and small offices than in the Netherlands, whereas in the Netherlands heating is mostly performed with gas-fired boilers and radiators at a high temperature level. The combination of these two reasons tends to make heating by means of heat pumps uneconomical in the Netherlands. For that reason cold storage is always dimensioned to supply cooling. An open-loop geothermal heat pump system will be dimensioned for the maximum demand (winter or summer).

Open-loop geothermal systems always include the use of a heat pump which serves as a chiller to supply the necessary cooling capacity. Generally, the heat pump provides the entire cooling capacity, with the groundwater merely being used to cool the condenser. With aquifer cold storage most of the cooling capacity is provided for by the groundwater through direct cooling (see e.g. Snijders, 1992). Where necessary, a chiller (or heat pump) can provide a certain degree of after-cooling to achieve the required temperature level. From the energy point of view, direct cooling is considerably more economical than operating a chiller (COP of 20 - 40 for direct cooling vs. a COP of 3 - 5 for chillers, see Table 1). Therefore, cooling with cold storage tends to bring about much higher energy savings in summer than cooling by means of an open-loop geothermal system.

Table 1 Overall COP* for different systems

System	approx. COP
Conventional air-cooled chiller	3
Groundwater-cooled heat pump running as a chiller	5
Open-loop geothermal pump, supply temperature 50ºC (120 ºF)	4
Direct cooling using cold storage - including electricity consumption for charging the storage (so without reuse of heat) - excluding electricity consumption for charging the storage	10 - 20 20 - 40

* Overall COP (Coefficient of Performance): amount of thermal energy delivered, divided by the total amount of electricity required.

In winter, open-loop geothermal systems make use of groundwater by extracting heat from it by means of the heat pump evaporator. With cold storage, the use of a heat pump is one of the options to charge cold energy. Other options include the use of cooling towers or the use of cooling coils in the air handling unit (AHU). In the latter case the stored heat can be reused to pre-heat ventilation air. With cold energy storage, the stored heat is not always reused. If the heat is not reused the total energy savings of a cold storage project may be lower than that of an open-loop geothermal heat pump system of similar size. Of course, this also depends on the COP of the heat pump and the energy balance of the system. When the cooling demand amply exceeds the heating demand (cooling-dominated system), the energy saving of a cold storage facility not reusing heat, will be greater than that of an open-loop geothermal heat pump system. In other cases (balanced and heating-dominated systems), the energy saving achieved with a geothermal heat pump system is greater than that achieved with cold storage without a heat pump.

This is shown in Table 2 for three examples; the figures given fully reflect the specific situation. In general, it may be concluded that, from the energy point of view, it will be attractive wherever possible to combine an open-loop geothermal system with cold storage and direct cooling. In addition to the above differences, the following aspects should be taken into consideration when applying cold storage:

- The amount of cold energy stored in the underground is finite. For that reason the winter cold must be utilized to the full to store sufficient cold energy. Major aspects to be taken into account are the thermal efficiency of the storage system and the tendency of increasing extraction temperatures from the source well from early summer towards the end of summer.
- The fact that the amount of underground-stored cold energy is finite, in most cases also means that a two-way flow control has to be applied to the cooling coils. This will minimize the amount of water pumped while maximizing the return temperature.

Table 2 Approximate fossil fuel consumption figures for different systems (GJ)

a. Situation of a balanced system: cooling demand = 1000 MWh (3600 GJ: 284,000 ton hours), heating demand on groundwater: 1000 MWh (3600 GJ; 3412 million BTU)			
	Heating (GJ)	Cooling (GJ)*	Total saving (GJ) vs. conventional
Conventional boiler and chiller	4235 ***	2667	-
Open-loop geothermal heat pump	2000	1600	3302
Cold storage without heat reuse	4235 ***	800	1867
Cold storage with heat reuse with heat pump	2000	400	4502
b. Situation of a cooling-dominated system: cooling demand = 1500 MWh, (5410 GJ, 426,000 ton hours), heating demand = 500 MWh (1800 GJ, 1706 million BTU).			
	Heating (GJ)	Cooling (GJ)*	Total saving (GJ) vs. conventional
Conventional boiler and chiller	2118 ***	4000	-
Open-loop geothermal heat pump	1000	2400	2718
Cold storage without heat reuse	2118 ***	1200	2800
Cold storage with reuse of 500 MWh of heat	1000	800 **	4318
c. Situation of heating-dominated system: cooling demand = 500 MWh (1800 GJ, 142,000 ton hours), heating demand = 1500 MWh (5410 GJ; 5118 milion BTU)			
	Heating (GJ)	Cooling (GJ)*	Total saving (GJ) vs. conventional
Conventional boiler and chiller	6353 ***	1333	-
Open-loop geothermal heat pump	3000	800	3886
Cold storage without heat reuse	6353 ***	400	933
Cold storage combined with geothermal heat pump	3000	200	4486

* Assuming an electricity generation efficiency of 45%, and assuming that all electric power is generated with fossil fuels

** One third with reuse of heat, two thirds without

*** Assuming a boiler efficiency of 85%

- As the costs of a well system mainly depend on the maximum flow, the difference between supply and return temperatures has to be maximized. This can be brought about by selecting a larger cooling battery than the usual size. To obtain the largest possible share of the cooling capacity from direct cooling (preferably 100%), the supply temperature for the cooled-water loop must be as high as possible.

- Direct cooling in summer considerably reduces the demand for the maximum electricity capacity, which is more than an open-loop geothermal heat pump system can do. If the peak in electricity demand occurs in summer, this is an additional advantage of cold storage.

There are several other major differences between the USA and the Netherlands as regards climate conditions and current interior climate requirements. As a first impression, however, outdoor conditions in the USA in summer are warmer and indoor conditions cooler. This results in a larger cooling demand and a higher cooling capacity per unit floor area. Consequently, cold storage for the same floor area can result in higher energy savings in the USA than in the Netherlands.

With hotter summers and an increasing cooling demand, more cold energy has to be stored. This requires the availability of sufficient hours with low outside air temperatures. One cannot really say something about this point for the USA as a whole, but for the state of New Jersey it has appeared that amply sufficient cold energy can be collected and stored in an average winter to cover the cooling demand in an average summer (Stiles et al., 1997). This also depends on the number of hours that this cooling load has to be met.

3. GROUNDWATER SYSTEM

3.1 Similarities

The two systems have in common that they use groundwater, which is pumped up from an aquifer through one or several source wells. Once the water has been chilled or heated, it is re-injected, generally into the same aquifer. In the past, the utilization of groundwater and its subsequent re-injection caused a number of problems. These problems, i.e. clogging of wells, breaching of confining layers and corrosion of ducts, can occur with both cold storage and open-loop geothermal systems. Thermal breakthrough between source and injection wells can also occur in both systems. All such problems can be prevented if the design is accurate, the realization is professional, and management is alert, and on the condition that a number of limiting factors are taken into account (Jenne et al., 1992).

3.2 Differences

Open-loop geothermal systems are based on the natural groundwater temperature, whereas the principle of cold storage is that groundwater is pumped from the underground at a temperature below the natural temperature in summer and above the natural temperature in winter. If there is no thermal breakthrough, it is easier for the system to start from the natural groundwater temperature. For that reason, cold storage is more complex. If the cooling system has been designed for a certain maximum extraction temperature below the natural temperature, this has to be done on the basis of sound calculations. The following aspects are to be taken into account:

- The amount of cold energy that can be collected and charged in a mild winter must be large enough to meet the cooling demand of a hot summer.
- The average injection temperature that can be achieved in winter must be sufficiently low, whereas it has to be taken into account that - in the course of summer - the extraction temperature from cold wells will gradually rise towards the natural temperature. The maximum extraction temperature to be expected largely depends on the amount of cold

energy charged compared with the amount of cold energy to be extracted, the regional groundwater flow, the temperature difference between the natural and charging temperatures, and the ratio between area and capacity of the storage facility.

For that reason the cold storage well field has to be dimensioned for the recovery of as much as possible cold energy at the lowest possible temperature level. Relevant factors are the amount of cold energy to be stored, the thickness of the aquifer, and the direction of regional flow. The situation for an open-loop geothermal system is different, where preventing the occurrence of a thermal breakthrough is the first criterion. For that reason, injection wells for open-loop geothermal heat pump systems will preferably be located downstream, with the largest possible distance between source and injection wells.

Most cold storage systems will use dual-purpose wells, which are both suitable for extraction and injection whereas most open-loop systems use single-purpose wells, equipped for extraction or injection only. The type of operation will have consequences for the design of the wells.

A major difference with the USA concerns groundwater flow rates; these are generally low (with 10 - 30 m/year; 30 - 90 ft/year) in the Netherlands, a fairly low-lying country, compared with the north-eastern states of the USA where groundwater flow rates of 100 - 300 m/year (300 - 900 ft/year) are usual values. For that reason, the regional groundwater flow is a more prominent factor in the USA.

An open-loop geothermal heat pump system will benefit from a high regional groundwater flow rate, but for a cold storage system this is not favourable. Major thermal losses from cold storage due to regional flow may be (partly) prevented by designing an adequate well configuration, for instance by:

- choosing an upstream location for cold wells to allow for cold-energy losses to be partly recovered in downstream warm wells;
- in case of several cold wells, arranging these wells in line with the regional flow, and injecting most of the cold energy into the uppermost well. In this way, a large part of the cold energy can be recovered from the most downstream well.

To realize the above optimizations, computer models are often applied to calculate the behaviour of water and thermal energy in the underground. If Technology uses the HST2D/3D model for such calculations (Bakema & Jellema, 1997).

The natural groundwater temperature is an essential factor for the performance of the system, whether it be an open-loop geothermal or an aquifer cold storage system. In the Netherlands, the natural temperature at a depth of 50 - 150 m (150 - 450 ft) below surface level often is 11 - 12°C (52 - 54°F). The natural groundwater temperature is dependent on the average outside air temperature in the period when most rainwater infiltrates into the soil, as well as on the temperature rise caused by geothermal energy between the infiltration area and the measuring point. In the Netherlands this results in a groundwater temperature in infiltration areas in shallow aquifers of approx. 10°C (50°F) which at a depth of 100 m (300 ft) below surface level may increase to approx. 13°C (55°F) in seepage areas.

In the USA, in the states of New York and New Jersey, the average outside air temperatures are higher than those in the Netherlands (partly the reason why the cooling demand is also higher in the USA), which means that the average groundwater temperature will be slightly higher. At the

Richard Stockton College, this temperature amounts to 13 - 14°C (55 - 57°F) at a depth of approx. 50 m (150 ft) below surface level.

Because of these differences under conditions which are quite similar in other aspects, cold storage will achieve a lower thermal efficiency in the USA. On the other hand, with such higher groundwater temperatures, heating by means of a heat pump is even more favourable.

4. ECONOMICS

4.1 Investments

The most prominent differences in investments to be made are:

- most wells for cold storage are dual-purpose wells, which are somewhat more expensive as each well has to be equipped with both a pump and an injection line;
- cold storage with direct cooling requires larger and consequently more expensive cooling coils;
- cold storage requires equipment to charge the cold storage. If this is a cooling tower (with gas boilers for heating) it is less expensive than when the same thermal capacity is installed as heat pumps. If the thermal energy is charged by means of heat pumps, the investments will be the same for similar capacities;
- cold storage requires a much smaller thermal capacity for the chillers (heat pumps) to be installed than open-loop geothermal systems. As a result, the investments for cold storage will be lower.

All in all this implies that - under Dutch conditions - considerably lower investments are needed for a cold storage system than for an open-loop geothermal heat pump system. This will be generally the same for the USA for those cases where natural gas is available. Morofsky (1994) also states that cold storage systems without heat pumps in general require lower investments and have shorter pay-out times than cold storage systems with heat pumps.

4.2 Exploitation costs

4.2.1 Energy costs

Cold storage used for cooling allows for a larger reduction in electricity demand than an open-loop geothermal heat pump system. On the other hand, in case of a large heating demand, a heat pump system will save more on primary energy than a cold storage system without reusing heat. Therefore, the economy of the two systems eventually depends on the heating demand and on the ratio between electricity rate and fossil fuel prices. If heating demand is high and electricity rates are low, a geothermal heat pump system will be very economical, whereas a cold storage system will be more favourable when heating demand is relatively low and electricity rates are high. To give an indication: the charge for electricity in the Netherlands is on average approx. 0.08 US$/kWh, which is comparable with the rate in New Jersey.

Yet, even if electricity rates are low and heating demand is high, altering an open-loop geothermal heat pump system into a cold storage system may still be considered. What measures are needed to do this?

- A reversible flow in the groundwater system: consequently a pump and several valves for adequately directing the flow.
- In summer the extracted cold groundwater should be used to directly cool the chilled water system prior to using it for condenser cooling.

These two measures only require modest additional investments but are capable of considerably raising the economy in energy consumption. And if direct cooling is applied, the heat pump capacity can be lowered, so that the investments can be even lower. However, for smaller systems it should be taken into consideration that the thermal efficiency of stored cold or warm energy could be low, especially in combination with high regional flow rates.

4.2.2 Maintenance

As far as can be concluded as yet, the costs of maintenance and management of a cold storage system are certainly not higher than those of a heat pump with groundwater-cooled condensers.

5. EXAMPLES OF COLD STORAGE IN THE USA

According to the information available to the author the number of projects in the USA with cold storage is low. The author has come across the following projects:
- Recreational Center at the University of Alabama in Tuscaloosa (Midkiff & Brett, 1994);
- Veterans Hospital in Tuscaloosa, Alabama (Brett & Midkiff, 1994);
- USPS mail processing facility at Melville, Long Island, NY, (Wilke, 1994).

It would be beyond the scope of this paper to give a detailed description of these projects. It should be noted, however, that both the Recreational Center project in Tuscaloosa and the Melville project have to deal with a large regional groundwater flow which was not anticipated. If this aspect had been taken into account at the design stage, it would have been possible to recover considerably more cold energy.

6. CONCLUSIONS

Energy saving achieved with cold storage invariably appears to be higher than with open-loop geothermal systems, provided that a heat pump is used for heating, also with cold storage. If heat is not reused in case of cold storage, cold storage is only more favourable from the energy point of view if the thermal energy demand is evidently cooling-dominated.

Regional groundwater flow rates in the north-eastern states of the USA are much higher than in the Netherlands. As a result, the application of cold storage in the USA demands that much attention is being paid to the hydrothermal calculations to optimize the well field and predict the efficiency of cold storage.

With the information available to the author at present, it seems justified to expect that in the USA it is economically attractive to combine open-loop geothermal heat pumps with thermal energy storage. The additional investments are relatively low or can be even negative, more energy is saved and the peak electricity demand is considerably lowered in summer. This applies in particular to the larger systems as these allow the thermal efficiency of thermal energy stored in the underground to be high.

REFERENCES

Bakema, G. and Jellema, I. 1997. The HST3D program for solving 3-D problems related to ATES. Megastock '97. Proceedings 7th international conference on thermal energy storage. Vol 2, pp. 835-840 Hokkaido University, Sapporo Japan.

Bakema, G. and Snijders, A.L. (1998). Field heating and space cooling at "Gelredome" multifunctional stadium in Arnhem; an example of heat-pump application in the Netherlands. Proceedings of the second Stockton international Geothermal Conference.

Brett, C.E. and Middkiff, K.C. 1994. Impediments to the commercialization of ATES Technology in the United States. Proceedings international symposium aquifer thermal energy storage. University of Alabama, Tuscaloosa, Alabama USA.

Jenne. E.A., Andersson, O. and Willemsen A. 1992. Well, hydrology and geochemistry problems encountered in ATES systems and their solutions. Proceedings 27th IECEC Conference. Volume 4, page 477-488. Society of Automotive Engineers, Warrendale, PA, USA.

Middkiff, K.C. and Brett, C.E. 1994. Longterm experience with an ATES based air conditioning system. Proceedings international symposium aquifer thermal energy storage. University of Alabama, Tuscaloosa, Alabame USA.

Morofsky, E.L. 1994. ATES energy efficiency, economics and the environment. Proceedings international symposium aquifer thermal energy storage. University of Alabama, Tuscaloosa, Alabama USA.

Snijders, A.L. Aquifer seasonal cold storage for space conditioning: some cost-effective applications. ASHRAE Transaction 1992 symposium, part 1; pp. 1015 – 1022.

Stiles, L.F., Hemphill, B. and Willemsen, A. 1997. Feasibility study on aquifer cold storage for West Quad, Recreation Centre and the Performing Arts Centre at the Richard Stockton College of New Jersey.

Wilke, D.A. 1994. Aquifer Thermal Energy Storage: a building block in integrated energy systems. Proceedings international symposium aquifer thermal energy storage. University of Alabama, Tuscaloosa, Alabama USA.

Willemsen, A., Bakema, G. and Snijders, A.L. States of cold storage in aquifers in The Netherlands in 1994. Proceedings international symposium aquifer thermal energy storage. University of Alabama, Tuscaloosa, Alabama USA.