Storing solar heat in a concentric store

Our homes are surrounded by energy sources (solar, the air, natural ground heat and waste heat) that have sufficient capacity to meet most of our energy needs and that cost us nothing for the energy itself. A previous article (City Block Systems) shows how these four local energy sources can be used in various ways to build local energy supply systems based on the principle of storing heat until it is needed. The challenge is to design collection/recovery systems that pay for themselves within a few years and that minimize the demand for electricity.

The average Ontario house uses 20,097 kWh for heating and 5,902 kWh for domestic hot water (DHW), for a total heat demand of 26,000 kWh. In principle you could use two heat pumps, one to extract heat from the ground to bring a home's air temperature to 22 degrees C (at a typical COP of 3) and the other to extract heat from that interior air to produce DHW at 60 degrees (at a typical COP of 2). That combination is not uncommon but it entails enlarging the size of the ground heat store to provide the larger capacity, plus purchase of a second heat pump for the DHW, and moreover the homeowner will need to provide nearly 11,600 kWh of electricity to drive the heat pumps. A minor variance is to use the first heat pump as a pre-heater for the hot water tank, using resistive electric heat to make up the difference at a lower capital cost but a higher running cost.

Another alternative is to use solar collectors to collect most of the 26,000 kWh total (less a small winter contribution that does not need to be stored because the collector provides some energy during the winter). The stored heat could be at a temperature that is high enough to provide all of the DHW and it might also provide a small part of the heat needed for space heating, again without needing a heat pump. However, if you extract much heat from the store then the temperature of the store will fall to the point where it would not be able to satisfy either need. For that reason the preferable method of recovering the heat to be used for space heating is to surround the injection site with a ring of boreholes at a distance that permits their operating temperature to cycle symmetrically above and below the ambient ground temperature, using a heat pump to deliver the heat to the home. Under those conditions nearly all of the collected solar heat will be put to good use.

The problems of that approach are that it requires a large solar thermal collector that is capable of collecting nearly 26,000 kWh, plus typically 400 metres of borehole (using U-tube ground heat exchangers) plus about 6000 kWh of electricity for the heat pump.

The City Block design achieves the same energy delivery but with a much smaller solar thermal collector that needs to deliver only about 9000 kWh, using a borehole length of only 80 metres and the same amount of electricity. Thus, both of these high temperature systems use only about half as much electricity as the variants that use only low temperature storage, but the City Block Design reduces the solar collector cost by a factor of 2.9 and the borehole cost by a factor of 5.0. Since those are the two major capital cost elements the cost advantage of the City Block design is huge.

The missing 20,000 kWh of energy is made up by heat extracted from the air and transferred into the ground (17,000 kWh) and the heat that flows out from the central borehole (about 3,000 kWh - see Storage Strategy). Air-heat exchangers are small, silent and inexpensive. That is the least expensive and most reliable means of collecting energy. It works even if there are no clear days all summer. The heat from the air-heat exchanger is fed to the middle ring of boreholes which is thermally isolated from both the central borehole and the outer ring of boreholes during the injection period because it takes six months for the heat to travel from one ring to its neighbours. In the second half of the winter heat is extracted from both the middle and outer rings. In general only a single borehole is needed at the center. A set of 13 boreholes that are 400 metres deep can supply 60 homes with space heating and DHW. The homes could optionally have Solar PV panels as well, in which case the potential power capacity would be 600 kW and the generation capacity would be about 480,000 kWh. The amount of energy supplied for space heating would be 1,200,000 kWh and for DHW it would be 360,000 kWh, bringing the total energy delivery of the facility to 2,040,000 kWh.

Storage Strategy

There are two different strategies that can be employed for storing the solar heat: 1) directing only surplus heat to the store or 2) directing all of the solar heat to the store. With the first strategy the temperature of the central ground store will be comparatively low so relatively little heat will flow out to be captured later for space heating. With the second strategy the ground temperature can be raised to nearly the DHW temperature so a much larger fraction of the solar heat will be used for space heating, but that implies that a larger solar collector will be needed in order to maintain the DHW supply. In both cases the replenishment water for the hot water tank can be pre-heated using the stored heat with any deficit being made up by electric heating so both strategies are comparable with respect to their energy efficiency

Both of these strategies are viable. With 1) the cost of the solar collectors is minimized and with 2) the cost of the ground store is minimized. A compromise between the two strategies can be achieved by setting the controls for 1) but increasing the size of the solar collector to feed more heat to the ground. With a large collector most of the heat would automatically go to the ground so the system would effectively be using strategy 2). This feature gives the system designer the ability to adjust the system capacity over a very wide range, including the ability to adjust the capacity even after the system has been built.

Increasing the solar contribution increases the system capacity in four ways:
1) the solar heat can be stored at a temperature that can range up to five times higher than the temperature of the air-heat storage region so the storage capacity rises with that temperature
2) the solar collector can deliver more than 50% of its summer output during the winter, so the need for storage is reduced
3) in the winter the coldest days are normally clear days so energy supply and demand tend to be synchronous
4) the central storage region holds a large amount of heat at a high temperature so it can maintain the DHW even during long cloudy periods and it can inject heat at the input of the heat pump during cold nights so the ground loop can be designed for the average winter demand rather than having to meet the worst case - the coldest night of the coldest year

The prototype City Block system drives a 25 kW heat pump with only 120 metres of ground loop, for a ratio of 208 watts per metre (or 4.8 metres per kW of capacity). That is about five times higher than the usual ratio for a ground source heat pump, and that ratio could be even higher if the solar contribution were increased (n.b. the 208 w/m ratio is achieved primarily via refinements in the ground loop and buffer design in the prototype, which does not yet incorporate solar heat storage).

Conclusion Integrating the air-source and solar thermal inputs into a concentric heat store is of benefit to both the space heating and DHW components of the system. Such systems will be very cost effective because they do not need either deep boreholes or large solar collectors.