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Optimized Design of Solar/Air Collection and Storage Systems for HVAC

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Abstract

A variety of hybrid or multi-source heat pump systems have been described in patents and academic literature, and are now beginning to be seen as commercial products. These systems often use solar thermal or related technologies. We describe here a comparison of several different methods to combine solar thermal collection with the collection of cold by means of convection and possibly night sky thermal radiation. Some of these cold collection methods are 1) the use of conventional unglazed solar thermal collectors; 2) a modification of the glazing surface designs of multi-pane windows. 3) the use of air to liquid heat exchangers (dry coolers). Another cold collection method (which is geographically restrictive) is the use of cold water deep in a lake, stream, river or ocean. This collection could be open loop or closed loop (heat exchanger in the water). We also describe herein several improvements in lower cost, long term storage of heat and cold underground. Extending the storage duration to six months will provide cost-effective seasonal storage. To gain the greatest advantage of what is described above, an optimized system of pumps, valves, and sensors will be used, along with computer control. Simulation results will be shown, along with examples of systems that have already demonstrated some aspects of the concepts herein. The end result of this type of system is the provision of both heating and cooling for buildings (either with or without the use of a water source heat pump), and in some cases the production of electricity, but without a need for direct use of fossil fuel.

Keywords: *Hybrid system, thermal energy storage, solar heat, geothermal heat pump, dry cooler*

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1. Introduction

Solar thermal collectors and related systems can play a very significant role in reducing energy use in buildings. Their use will be determined by the building size, shape, and available nearby area for collector installation. The largest and tallest buildings have a lesser possibility for near term solar thermal use, but the opposite is true for all buildings that have a relatively large roof or parking lot area nearby. Some types of solar thermal collectors have a dual use, whereby they can collect cold as well as heat, using night sky radiation and/or convection as the mechanism for cooling (Anderson et al., 2011 and 2013; Man et al., 2011). Also, for similar functionality, a dry fluid cooler can also be used to collect either heat or cold. Each of these choices has a set of advantages and disadvantages, which need to be evaluated. In some cases the collection of heat and/or cold with passive methods will be sufficient for space conditioning of buildings such as those with passive house designs (Fokaides et al., 2016; Whang and Kim, 2014; Chen et al., 2015). In other situations, a heat pump will be needed to give sufficiently high or low temperatures and also adequate thermal capacity. Another important consideration is the selection and optimization of thermal storage. This might be done with water tanks, ice storage, or underground (using the earth as the storage medium) (Olson and Yu, 2016). All of the choices above lead to a challenging optimization task to find the most cost-effective selection of thermal elements along with optimized designs for interconnection and control. This paper aims to introduce and demonstrate the optimized design and the combined use of above-mentioned energy-saving measures for building heating and cooling. This optimized design contributes to the use of renewable energy, maximizing system efficiencies and entirely eliminating fossil fuel use in buildings. Additionally, this paper is intended to explore the best practices in the integrated design of building Heating, Ventilating, and Air Conditioning (HVAC) systems.

2. Solar thermal collector selection

Solar thermal energy is a common source for space heating, which can be obtained using solar thermal collectors. In considering this topic it is important to recognize the different types of collectors that could be used. There are four types that can be considered for use with buildings:

- Glazed flat plate collectors - these usually have a metal absorber plate with fluid channels spaced several centimeters below a glass window or glazing surface.
- Evacuated tube collectors - these use an array of glass cylinders within which is a vacuum for insulation and an absorber surface to allow for heating of either water or other specialized heat exchange fluid.
- Unglazed collectors - these consist of black plastic absorber surfaces or cylinder arrays that have water or antifreeze fluid flowing in small diameter channels but no glass window.
- Concentrating collectors - these generally use moving reflective surfaces to maintain an optimum pointing angle relative to the direction of the sun. The most common types use moving parabolic cross-section reflectors.

The first three types above are by far the most likely to be used with buildings for HVAC systems. The concentrating collectors are more likely to be used in desert areas for generating steam for either industrial processing or electricity generation, however, there is some use of this collector type for small scale and/or rooftop installations (www.absolicon.com). A good overview of the comparisons and details of construction and use of these collectors can be found in Solar Thermal Collector (2017).

Of course there are other references/books (Hadorn, 2015; Duffie and Beckman, 2013; Gordon, 2013) that also cover solar thermal technology in great detail. The goal for this document is to suggest what might be the most cost-effective way to put this technology to use in buildings for HVAC and what combinations of other related technology can be synergistic in this use. It should be recognized that for any given rooftop or ground area, there may be competition between advocates of solar electricity generation and solar thermal generation. There are three important facts that should be kept in mind for this comparison:

- Solar electricity will be much less expensive when it comes from a large array on an open field somewhere away from a city. The largest open field arrays for solar electricity generation are half the cost of small rooftop generation for a given amount of power.
- Solar electricity placed on the power grid can be transferred over many hundreds of miles with negligible loss. The same is not true for solar thermal energy.
- From a fundamental energy conversion standpoint, solar thermal collectors can convert sunlight to thermal energy with nearly 100 percent efficiency. Solar photo-voltaic (PV) generation is typically less than 20 percent efficient.

These facts lead to the conclusion that rooftops and nearby ground areas might be best used for solar thermal collection and not for solar PV electricity. With the expansion across the U.S. of community solar farms, ownership of solar PV generation can be extended to everyone, regardless of rooftop ownership.

Solar thermal energy has two general types of use in buildings, i.e., domestic hot water (sinks, showers, laundry, kitchen, etc.) and space heating or HVAC.

These two uses will have different temperature requirements, and may determine what types of collectors can be used. Of the first three collector types in the list above, evacuated tubes have by far the highest temperature capability, and are also useful over more months of the year. They will produce hot water whenever the sun shines and are not greatly affected by cold wind.

Unglazed collectors do not have good performance at high temperatures and are affected by cold wind, but they are the least expensive per unit area. Their greatest use at present is for swimming pool heating. For space conditioning applications they have the benefit of being able to collect either heat or cold. For cold collection their use can be either seasonal (collecting winter cold for use in summer) or diurnal (collecting night-time cold for use during the next warm afternoon). This is being done currently in New Mexico (SolarLogic, 2017).

Glazed flat plate collectors have characteristics and cost in between the two types mentioned above and are very widely used for both domestic hot water and space heating. The largest solar thermal collector array in the world uses glazed flat plate collectors, and is located in Silkeborg, Denmark (Epp, 2017).

Other useful reference books for solar thermal comparisons and installation guidelines include Siegenthaler, 2016, Skinner et al., 2011, Walker, 2013, and Hadorn et al., 2015.

The graph in Fig. 1 shows a thermal output power of 600 watts per square meter at a temperature difference of -15 K. Since the solar input power is only 500 watts per square meter this appears to be an efficiency of 120 percent. The explanation for this is that energy is collected by the unglazed collector in two different ways:

- Conversion of sunlight incident on the collector into thermal energy.
- Convection transfer from relatively warm air blowing across the collector into thermal energy of the internal liquid.

Although each transfer method above is less than 100 percent efficient, the sum of both is greater than 100 percent. Notice, however that with zero temperature difference, both collector types are about 80 percent efficient. This is four times greater than a typical PV collector.

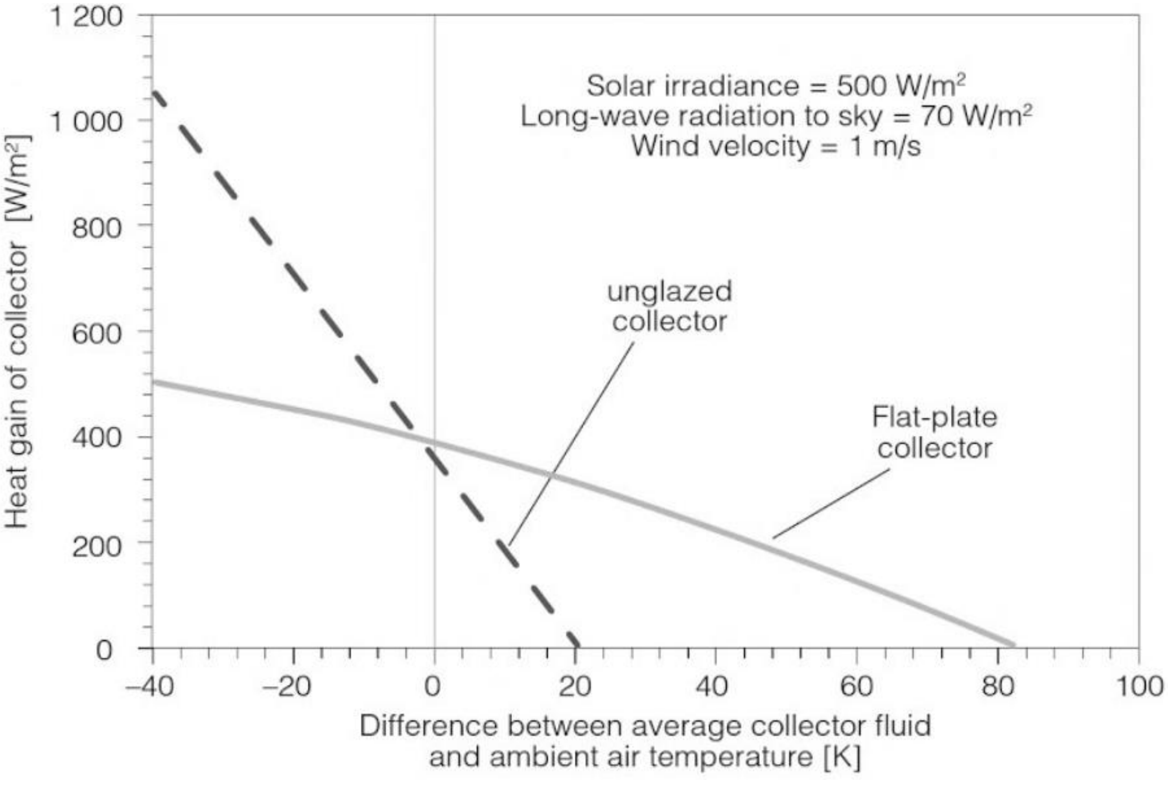

Fig. 1: Solar Thermal Collector Performance (Hadorn et al., 2015)

3. Design Integration

For the best possible use of solar thermal collection, consideration should be given to the combinations possible in systems also using water source heat pumps (or heat recovery chillers) and underground heat exchange or storage. There have been many versions of these combinations described in books, patents, and actual use (www.thermselect.de) over many years (Olson and Yu, 2016; Bottarelli et al., 2016; Jeong et al., 2017). One such combination of technology is shown in Fig. 2.

The flow paths for the system in Fig. 2 are assumed to contain either water or antifreeze solution and the heat pumps are assumed to be conventional water source units, available from many suppliers worldwide. On a larger scale, the heat pumps could be called heat recovery chillers, but the functionality is similar. The system in Fig. 2 is relatively simple, needing only two valves and four variable speed water pumps. A further assumption is that there will be multiple temperature and flow rate sensors in the system and a computer for control and optimization.

The horizontal ground loop in Fig. 2 is assumed to be a type suitable for very long term thermal storage in the earth (at least three months). This type of storage will be optimized if there is a fluid connection at the center and one or more connections at the perimeter. Examples similar to this can be found at Drake Landing Solar Community (www.dlsc.ca) and Seasonal Storage Technologies (www.sstusa.net). Similar examples with seasonal storage but without a central point connection are shown at ICAX (www.icax.co.uk) and a more general treatment of seasonal storage is described in STES, 2017.

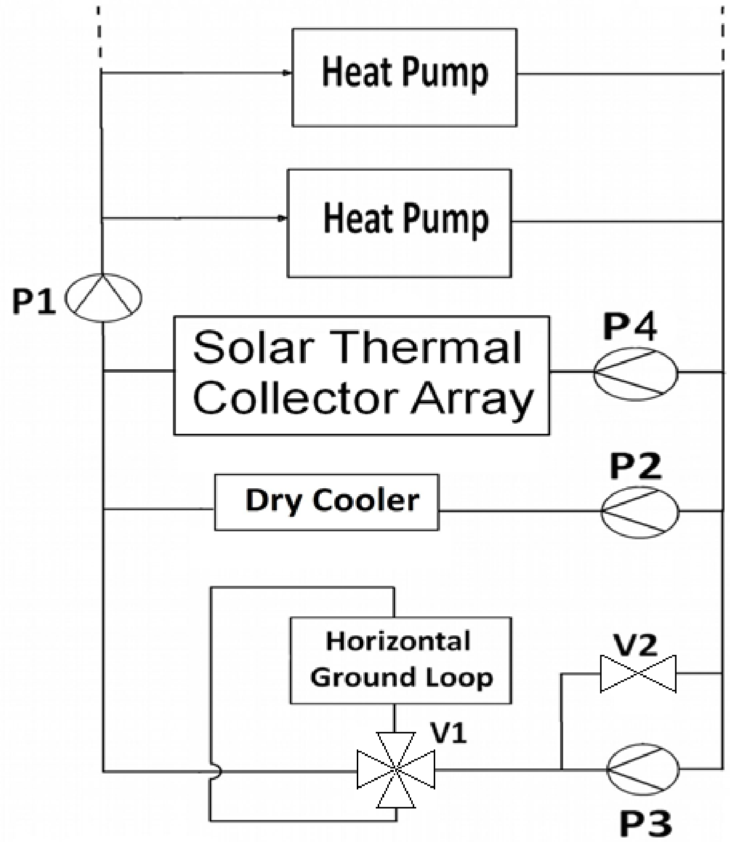

Fig. 2 Hybrid or Multi-source Heat Pump System

If a central point connection is not used, the valve V1 in Fig. 2 can be eliminated. For the smallest size building to be considered, perhaps the ground loop in the figure above could be changed to one or two boreholes or standing column wells. Again, in this case, valve V1 is not needed. In this case the system still has the multi-source advantage, but loses much of the seasonal storage advantage. Seasonal storage is important because solar heat is mostly available in the summer months, but is most needed in the winter months.

The specific component selections in the hybrid heat pump system above will depend on whether the building being conditioned is heating dominated or cooling dominated. That is, over a full year, is more energy expended doing wintertime heating, or is more energy needed for summertime cooling. If more heating is needed, the best collector type is likely either glazed flat plate or evacuated tubes. On the other hand, if more cooling is needed, the best collector is likely to be the less expensive unglazed type. The unglazed collectors will serve as air to liquid heat exchangers as well as solar thermal collectors. For a system in a cooling dominant climate, Fig. 2 could be simplified by eliminating all solar collection. Similarly, for a system in a heating dominant climate, the dry cooler could be eliminated.

What is described above provides four specific benefits beyond standard HVAC practice today:

- The system allows an immediate selection between a ground source mode and an air/solar source mode depending on the temperature from each source. Since air and solar collector temperatures have a much greater variation compared to underground temperature, the average heat pump efficiency is significantly improved.
- If only horizontal pipe arrays are used, the installation cost can be much lower than is the case for borehole heat exchangers.
- With a water connection at the center of the underground pipe array region, the long term thermal storage capability is greater than for the case with connections only at the perimeter.
- The system as described here can force the ground to be rapidly cooled in the spring shoulder season and rapidly warmed in the fall shoulder season. This would be done by using a preconditioning mode with only water pumping and also judicious selection of ground source heat pump mode when the transfer of heat is in the right direction. If the transfer of heat is in the wrong direction, the air/solar mode would be used.

Although not shown in Fig. 2, another improvement in the system could be the use of ice storage tanks (www.calmac.com). With ice storage in the system, one or more of the heat pumps could use fluid coming from the unglazed collectors or the dry cooler as the source fluid to make ice in the middle of the night in summer. The following day, the ice provides air conditioning using only water pumps for cold water circulation.

Other than ice storage tanks, a water storage tank or tanks could also be part of the system. If domestic hot water is to be the principal use for solar thermal collection, perhaps one or more water tanks will be all that is needed to complete the system. Of course the use of solar thermal collection for both space heating and domestic water heating will lead to much greater reduction in fossil fuel use.

Looking to the more distant future, all buildings that have windows may be able to use some of the ideas above to reduce or eliminate fossil fuel energy. A starting point for this is research now being done on the conversion of windows into solar thermal collectors and/or air to liquid heat exchangers (www.fluidglass.eu).

A more ambitious system using many of the concepts above is shown in Fig. 3. Fig. 3 shows a solar thermal collector at the upper left, a horizontal pipe array at the upper right, and a permanent source of cold water at the lower right. The horizontal pipe array would be placed below a horizontal insulation layer to avoid heat exchange in an upwards direction. It could be placed below a building during construction with dimensions to match the building. Depending on building insulation and size parameters, additional capacity could be obtained by using one or more borehole heat exchangers at the center. The source of cooling in Fig. 3 is for locations in climate zones where the maximum density temperature of deep water (39 degrees F) persists for most or all of the year. This is the case for Cornell University in NY and Toronto in Canada (DWSC, 2017).

The assumption in Fig. 3 is that a closed loop heat exchanger will be used to obtain cold water. With a permanent source of hot water and a permanent source of cold water, electricity generation is possible using an Organic Rankine Cycle (ORC) system as is also shown in Fig. 3.

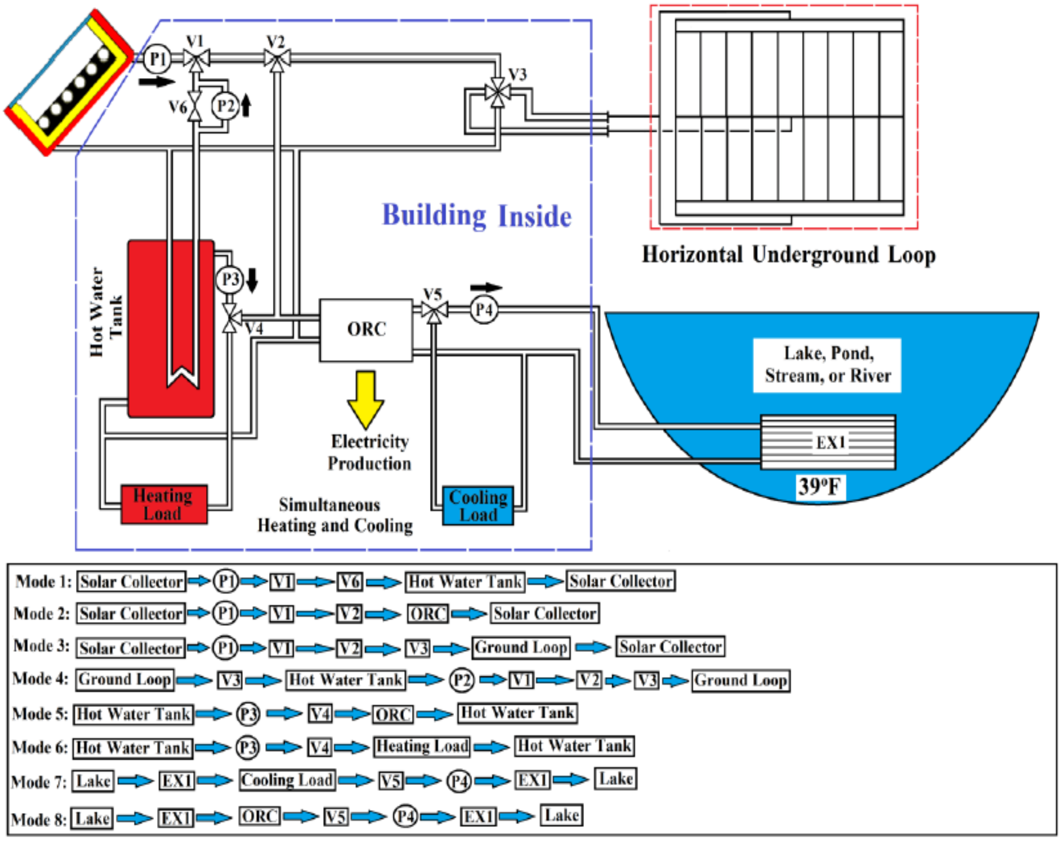

Fig. 3 HVAC System with Seasonal Storage and Electricity Generation

4.   Underground Thermal Storage

Underground loops have the ability to convey thermal energy to the ground and thus allow a long term thermal storage in the earth. In order to evaluate the capability of underground thermal storage, computer simulations were performed in this study, whose results are shown in Fig. 5. The assumptions going in to this figure are that there is a heated device below a large area surface insulator with ground thermal characteristics as listed at the bottom right corner of Fig. 4. In these simulation studies, various underground region shapes (cube/rectangular block/hemisphere/sphere) were involved, indicating different ways to design and bury underground loops and thus representing the shapes of the underground regions that are affected by the underground loops (Fig. 4). Additionally, different simulation tools (LISA - FEA and COMSOL Multiphysics – Heat Transfer module) were used in order to avoid unnecessary errors caused by the incapability of any of the simulation tools. In order to approximate a seasonal time frame, the heating device buried underground is assumed to be turned on for 60 days followed by a 150 day cool down time. During this 150 day period, a certain fraction of the initial heat will be lost to the surrounding ground. As shown in Fig. 5, as the increase of the dimensions (the ratio of Volume to Area) of the underground regions affected by underground loops, the heat/energy retention ratios that represent the ability of the thermal storage of the underground regions are raised. When the Volume/Area ratio equals to 5, the corresponding retention ratios are between 50% and 80%, with the average of 70%, regardless of the underground shapes or simulation tools. This demonstrates the capability of the earth to store thermal energy as long as the affected underground regions are large enough. More detailed studies are underway, whose results will be demonstrated in the future.

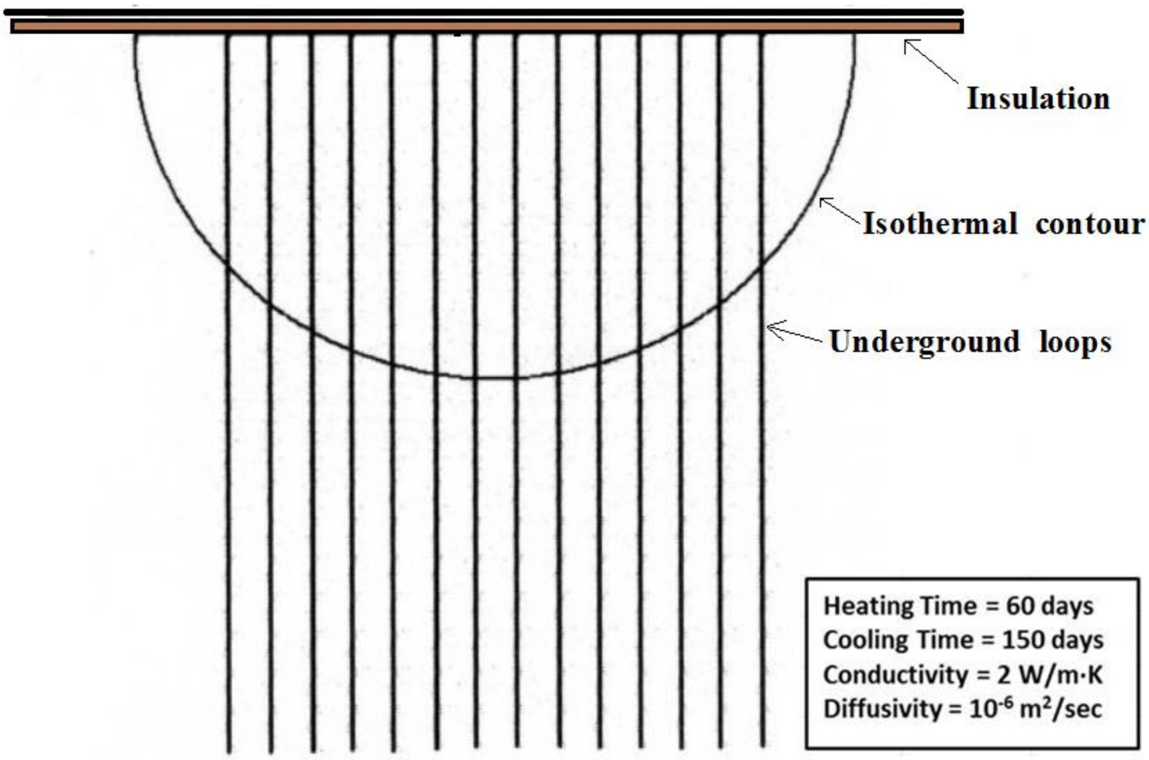

Fig. 4 Underground thermal storage simulation

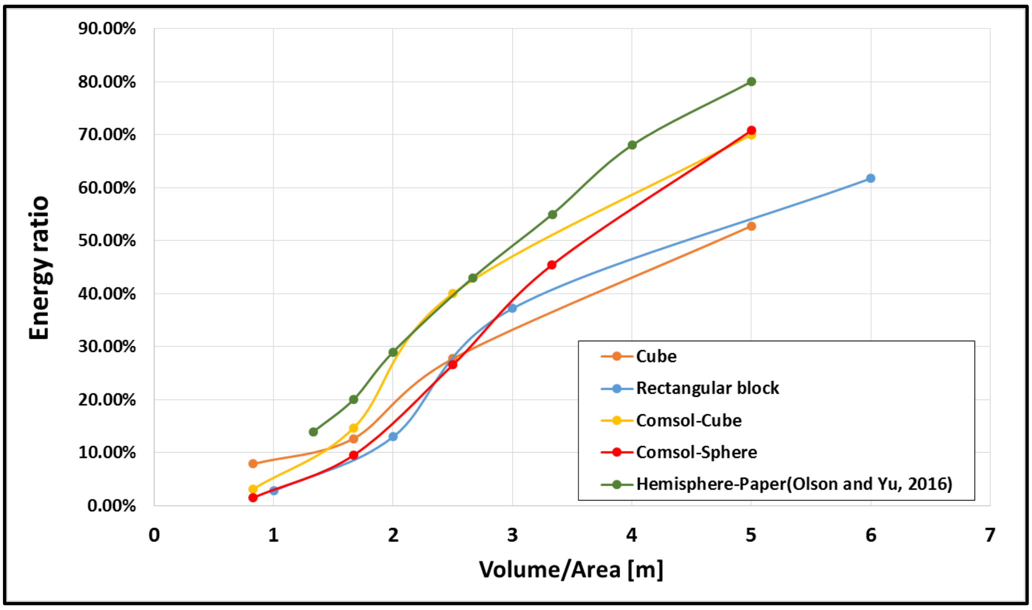

Fig. 5 Underground heat/energy retention ratio

5. Conclusion

In summary, a variety of solar thermal collector types and related technology might significantly reduce fossil fuel energy use in buildings. Over the near term, the best possibility is for buildings that have a large enough roof area or have nearby surface area that is large enough for installation of either a horizontal or vertical ground source heat exchanger. Over the longer term (5 to 10 years), solar thermal collection and air to liquid heat exchange might be extended to any and all buildings that contain windows. This might eventually include high rise buildings in any city.

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