SUSTAINABLE TECHNOLOGIES FOR OVERVIEW OF PROTOTYPE GREEN-BUILT HOUSE DESIGN

R. Wayne Guy[1] and Paul Tinari[2]

INTRODUCTION

Guy Architects, Ltd. reviewed the ways in which green technologies could be incorporated into the general housing market. The following is a review of sustainable technologies we considered for incorporation into a prototype housing design. The litmus test for the selections of systems included the following:

- *Are the systems easy to maintain?*
- *Are the materials durable and the layouts flexible?*
- *Does the design have curb appeal to attract a broad range of homeowners?*
- *Does the design encourage a more widespread use of Green Design principals in the construction sector?*
- *Does the design use familiar off-the-shelf technology?*

The prototype was designed for southern Canada where farms and industry are available to provide the materials needed for the unit's mass production. The design incorporates long-lasting materials to extend the building life to an estimated 80 years. By doing this, the house could provide multi-generation abodes for families, while amortising the initial cost of the unit over a longer period of time. The flexible plan has dynamic spaces, which can accommodate a variety of lot orientations. We anticipate that the unit's construction cost would be between $200K and $300K, depending on the configuration.

Flexible Planning

Though the base design is a 4-bedroom unit; the footprint can accommodate between 2 and 6 bedrooms. The plan can be configured into row housing to fit on a 40-ft × 100-ft lot or a detached unit on a 50-ft × 120-ft lot. The garage area can be modified into a 2-story greenhouse with a mezzanine sunroom with a 16-ft. high, south-facing translucent polycarbonate overhead door. The garage can also be used as a family room or a recreation room accommodating billiards or table tennis with a roof deck on top.

Flexible Orientation and Easy Public Amenities

The house can accommodate vehicular and pedestrian access from both the north and the south, as there are translucent, overhead doors at both end of the garage. This means a favorable orientation for the large, south-facing Trombe wall can be maintained for units located on both sides of an east-west street. By mirroring the plan, the driveways for the two units can be used as a play area for basketball or hockey. To the rear of every lot, bike and pedestrian trails tie into a community amenity such as a park. Native species of planting have been used for landscaping. Species include cedar placed on the north side of the building for a windbreak; late foliage trees such as ash on the south for seasonal sun control, and wetland planting at the sides of the house for run-off control. A typical subdivision design for a site outside of Toronto was prepared using the prototype layout in a variety of configurations.

Mass Production and Green Components

Straw bales have been used for the exterior walls for an approximate R-35 thermal resistance value. This product is cheap and readily available from local farms. The roof assembly is made up of wood trusses, recycled cellulose insulation, and zinc roofing. A concrete slab on steel decking has been used for the floor structure and incorporates recycled crushed glass for aggregate to reduce landfill. A light steel post and beam structure supports the slabs. The structure is bolted together for easy on-site erection and easy demolition, making

1. Guy Architects Ltd., www.guyarchitects.com. Mr. Guy may be reached at (867) 873-3266 or wayne@guyarchitects.com.
2. P. Eng., The Pacific Institute for Advanced Studies.

these structural components reusable in future building. The polished concrete slab would be exposed in most of the unit, providing an aesthetically pleasing finish free of the off-gassing found in engineered wood products. Steel studs and paperless drywall are used for the interior partitions. The removal of paper from the wallboard eliminates a food source for moulds, while the steel studs can be recycled at the end of the building's life. The windows and the south-facing curtain wall have thermally-broken aluminium frames with double pane low-e glazing. All the material for this building has been selected for economy and durability.

SOLAR HEATING

Passive Energy Collection Using a Trombe Wall

In the design, passive includes:

1. Collector—curtain wall, windows and dark walls.
2. Storage—Trombe wall originally described by Trombe, et al. (1976) and floor slab. Large interior thermal masses irradiated by sunlight in the colder months.
3. Distribution system—radiation lines in Trombe wall and slab, free convection, simple circulation fans.
4. Controls—moving insulation panels to control building or collector heat loss, vents, and windows. These are manually operated.
5. Backup system—ground source heat pump.

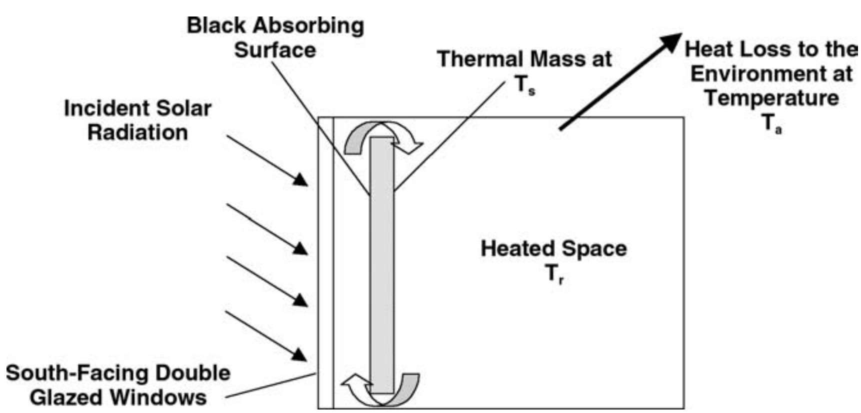
The design of passive systems uses a south-facing curtain wall. Behind one-half of the curtain wall is a concrete Trombe wall. The remaining portion of the wall lets light and view into a 2-story high living and dining space. This volume, aside from being a dramatic architectural feature, also distributes heated air to the north side of the house.

A large concrete mass 0.40 m in thickness is exposed to sunlight through the large south-facing curtain wall. Sunlight absorbed on the surface of the thermal mass is transferred to the interior of the storage mass by conduction or convection from the surface as shown. In addition, some re-radiated thermal energy is transferred to the environment through the glass wall. The heated air rises by natural convection and passes into the heated space through the upper air vent.

The thermo-circulation vents (see above), located at the bottom and top of the wall, are roughly of equal size. Their purpose is to permit the natural thermo-circulation of the air from the heated space (T_w > 140°F) to the living spaces (T_r = 70°F). The natural flow of air will continue for about 2–3 hours after sunset, until the external wall surface temperature becomes too cool to induce warm airflow. The total area of the vents should roughly be equal to 1 ft.^{2} for each 100 ft.^{2} of wall area. Reverse airflow at night is prevented by placing a manual or automatic damper over the inside face of the upper vent(s). Furthermore, placing removable insulation over the glazing at night or during periods of no sunlight significantly increases the overall efficiency of the system by reducing potentially large losses through the glass.

Heat stored in the thermal-mass wall is radiated and convected into the space to be heated. During the summer, vents at the top of the south-facing wall

Schematic of a Trombe-type passive solar-heating system showing the passive collection device and the storage mass. The south-facing transparent wall can be insulated during periods of no sun to reduce heat loss.



may be opened, and the warm concrete wall can create a chimney effect to enhance ventilation.

The diagram below shows a schematic of an equivalent thermal circuit for the highly simplified building model shown above. Three temperature nodes are identified here—room temperature, storage temperature, and ambient temperature. The circuit responds, here-room to climatic variables represented by a current injection I_s (solar radiation) and by the ambient temperature T_a. The storage temperature T_s and the room temperature T_r are determined by current flows in the equivalent circuit.

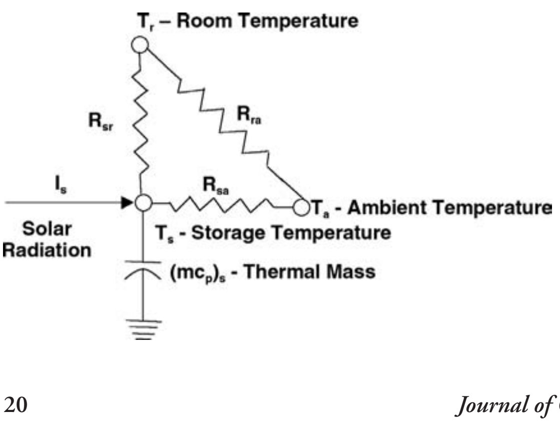
COMPOSTING TOILETS

Composting toilets are systems that treat human waste by composting and dehydration to produce a useable end-product that can be a valuable soil additive. They come in a variety of models and brand names, as well as different shapes and designs, to enhance and optimize the natural composting process. They use little or no water, and they do not need to be connected to expensive centralized sewage systems; therefore, no piping is required. They cause no environmental damage and they produce a valuable resource for gardening.

We selected composting toilets for use in the prototype house for the following advantages:

Unusual Sites. Composting toilets can be installed in many different situations that would not accommodate other systems, such as sites that are rocky or swampy, have a high water table or no water storage, are environmentally sensitive, or are close to running watercourses. All these difficult site situations can be accommodated with a small amount of alteration to the basic system design.

Equivalent thermal circuit for passively-heated solar structure.



Reduction of Odour Problems. The suction air flow in most composting systems takes toilet and bathroom odour out of the room and acts as a constant extraction fan.

End Product Recycled. While it is small in volume, the solid end product is a valuable humic fertilizer that can be utilized around trees and gardens.

Reduced Grey Water Loading. Where composting toilets are installed instead of septic or mini-treatment systems, there is a large reduction in the "loading" on the effluent treatment system by the removal of "black-water." Smaller, lower maintenance grey-water systems can, therefore, be used.

Recycling. A composting system offers the capacity to recycle a significant amount of the household waste. Food scraps, paper, lawn clippings, and grease from grease traps, using a grey-water system—can be composted back through the toilet. If a reed bed grey-water system is installed and is available, then a complete wastewater treatment system is possible at relatively low cost. There is no wastage in the system.

Reduced Marine Pollution. Nutrient load on surrounding streams and rivers are almost negligible using a composting system. This results in more oxygen being available in the water and a return to improved activity of marine life.

Less Environmental Impact. Compared to centralized sewage systems, on-site composting and grey-water treatment has less impact on the environment:

- Large effluent releases and other discharges into watercourses and oceans are avoided.
- Disruption to the environment through piping installation is eliminated.
- Leakage of raw sewage into groundwater through pipe deterioration and breakage is eliminated.

Flexibility in Estate Planning. By eliminating the planning constraints of the sewage system's underground piping and infrastructure, housing developments can be designed with more emphasis on environmental and social considerations, rather than how to best situate the blocks to make pipes run straighter.

All composting toilets carry out this basic process of aerobic decomposition. Design variations have been developed to enhance this process and they include:

- Baffles for increasing the efficiency of air distribution in the pile.
- Heating elements to keep the compost at the optimum temperature.
- Injecting air for increasing the decomposition rate.
- Mixing tongs to ensure homogeneous decomposition throughout the pile.
- The addition of composting worms and macro-organisms to speed treatment.

There are a wide variety of systems including:

- Owner-built, two chamber composting systems that are simple, but effective.
- Owner-built from concrete blocks and with a concrete-lined, inclined base. These systems are constructed inside the house's foundations.
- Manufactured, large tank, inclined base models suitable for heavy loadings.
- Wide variety of small units that fit into existing bathrooms. Many of these units come equipped with dehydration fans and heaters.
- Vacuum flush units for the production of worm castings.
- Full flush systems with centrifugal action to deposit wastes into composting chamber.

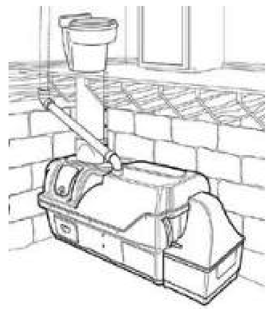
There are two types of systems, the Batch System and the Continual Process System. With the batch system, a container is filled and then replaced with an empty container. The composting process is completed inside the sealed container. The system may have a single replaceable container, or it may be a carousel system where three or four containers are mounted on a carousel. A new container is spun into the toilet area when the other is full. After a full cycle is completed, the first container is fully composted and ready for emptying.

With the continual process system, material is in a constant state of composting. "Deposits" are put into the system, composting reduces the volume and moves it downward where it is harvested after 6–12 months as fully composted material. All systems are designed to treat the organic "deposits" by composting, worm processing, micro- and macro-organism breakdown and dehydration and evaporation of moisture.

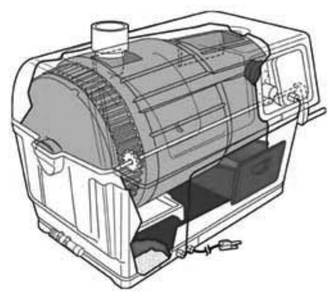
We selected a continual process system for our prototype design for the advantages mentioned above and the fact that the system is viable within a LEED standard green building.

System Diagrams

The schematic shown below represents a typical installation of a composting toilet system. The composting chamber must be mounted directly below the toilet. The purpose of the composting chamber is to maintain optimum conditions for the micro-organisms responsible for composting waste.



The commercially available composting unit, shown below, contains a rotating drum to constantly mix the contents of the chamber so that all of the organic wastes are completely aerated.



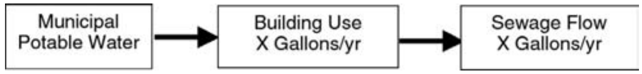
WATER MANAGEMENT SYSTEM

All water and wastewater that flows into and out of the building can be managed as a closed system. Most locations in Canada will receive from 50 to 125 cm of rain per year. Rainwater captured from the roof of most single family structures will be able to provide about 100 m^3 of fresh water per year. Therefore, it is possible for reclaimed rainwater to supply at least a significant portion of the total water needs of a typical LEED standard green building with the use of medium sized storage tanks. Lower water using fixtures are used for sinks and showers with a flow rate of about 0.5 U.S. gallons per minute (gpm). With potable water at a premium, the best conservation scheme is to use non-potable water for landscape irrigation. This is accomplished through a combination of rainwater, municipal supplied water or pumped groundwater (if available), and water from treated grey water produced by the on-site biofilter. This system has a 100% separation of potable and non-potable in all pipes and storage tanks. The addition of water storage tanks to the building design adds some additional costs to the construction, but also provides a number of benefits. For example, the inherent coolness of the water means that water can be circulated through the building's cooling system as a low cost way of cooling the building in summer.

Waste Water Treatment

The first step in wastewater treatment is to minimize the volume of wastewater that has to be processed in the first place. The second step is to re-use as much of the processed water as possible within the building for applications such as toilet and urinal flushing and landscape irrigation. Reusing the reclaimed water for toilet and urinal flushing requires water treated to Class 4 standards—essentially drinking water standards.

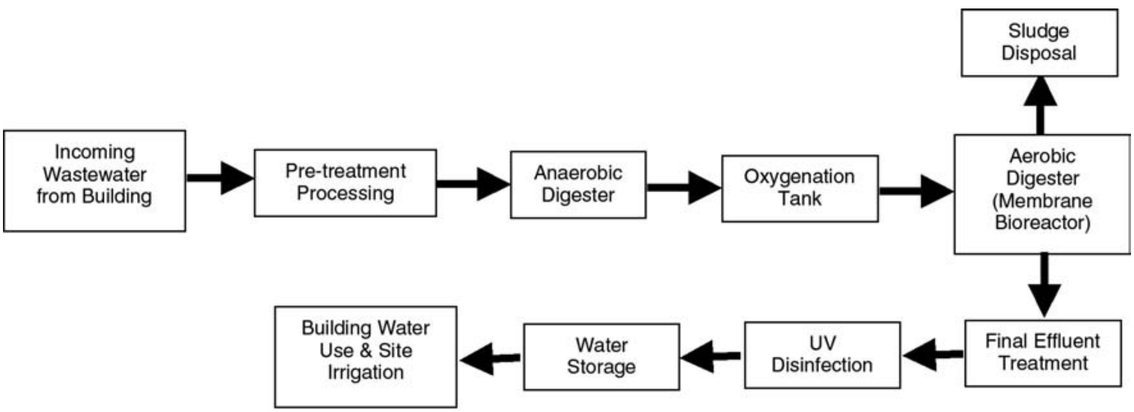
In a conventional building, the water use can be represented as follows:



Conventional buildings operate totally on potable water, typically treated and filtered, for moving human and food preparation waste out of the building into the sewer system. In many urban areas, there is a long-standing problem of combined sewer overflows during periods of higher-than-average rainfall, which means that every new building without on-site water recycling adds to the pollution of nearby natural bodies of water.

The Prototype wastewater treatment system is located in the basement of the building and will be hooked up to a septic system or the local sewer system in case of emergency overflow or for periodic sludge discharge. The system is designed so that the treatment process requires very little occupant attention. With the exception of solids (sludge) discharge and an annual membrane cleanout, the system can operate virtually unattended.

The sewage treatment plant has to provide both anaerobic and aerobic treatment of wastes, before final polishing and disinfection. The resulting Class 4 water will be of drinking water quality. A small amount of sewage solids needs to be discarded on a periodic basis. The complete bioreactor flow diagram is shown.



Complete Building Bioreactor Wastewater Treatment System

The main problem with the above comprehensive system is that it is very hard to justify the significant added expense for a single-family habitation. For this reason, this type of system is usually only justifiable in larger commercial buildings and not for single-family homes. The better and more economical approach is used in the prototype in which composting toilets treat sewage wastes, and a water biofilter treats grey water. Our system is described below.

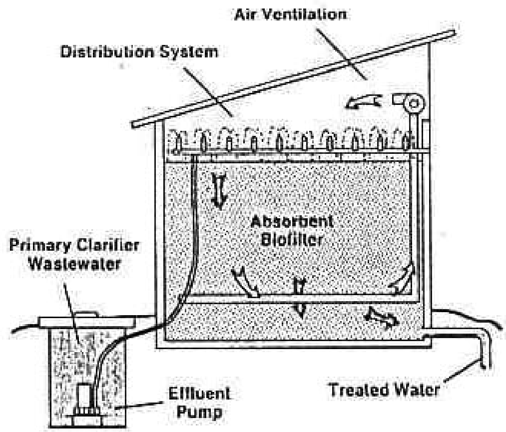
Each building, green-built or not, will produce a significant volume of non-septic wastewater each day from showers, baths, and sinks. While the daily volume of grey water is significantly reduced in green buildings, careful consideration must still be given to the on-site treatment of this liquid waste product. While it is not necessary to treat this water to the same extent as sewage, this grey water should not be discharged directly to the environment without some treatment. In fact, LEED standards require that all of the grey water produced by the building be recycled and reused on site.

Pre-manufactured mechanized systems are independent of the environment and will perform consistently if continually maintained. However, this maintenance is more than the typical homeowner (or organization) is willing to undertake, and treatment performance may be compromised.

Consistent with the low-maintenance, appropriate-technology focus desired by our team, we proposed a single pass biofilter be developed to provide consistent aerobic renovation independent of the environment, with low effort and with virtually no maintenance requirements.

The Absorbent Biofilter renovates domestic grey water in a small contained volume because of the particular physical properties of the synthetic filter medium. In contrast to soil and sand media, which must be loaded with wastewater, allowed to drain and then allowed to aerate before loading again, the medium provides separate flow paths for wastewater and air. This characteristic enables simultaneous loading and ventilation, which in turn permits much higher loads of waste water compared to a tile bed or sand filter, without sacrificing effluent quality. The medium readily handles surge flows and does not plug even at high loading rates. A diagram of the system is shown in the next column.

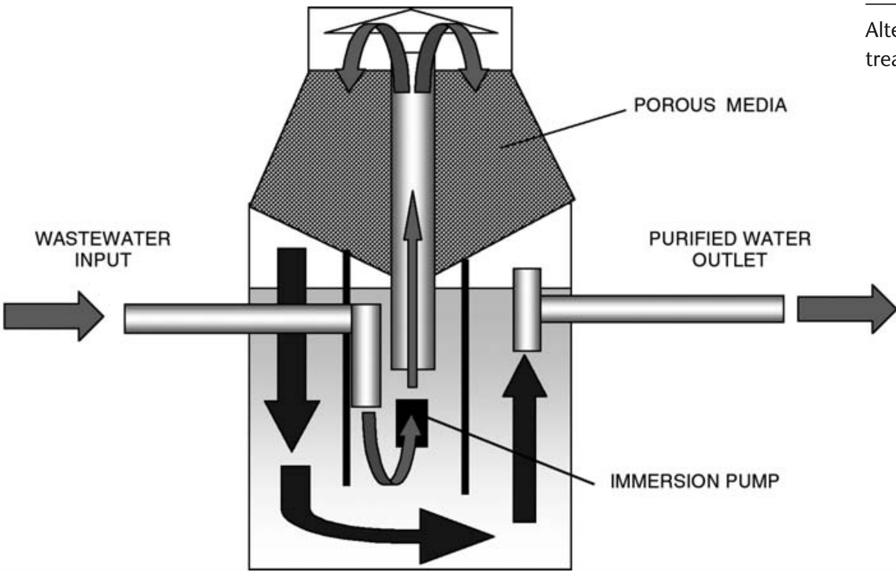
The biofilter is contained in a covered fibreglass or concrete tank and is insulated with Styrofoam



sheets. A small fan circulates air through the medium by way of ventilation pipes. The biofilter medium is about 1 m thick. Tests have demonstrated that this biofilter is capable of removing an average of 97% of TSS in the effluent at a loading rate of >1,500 L/day. The BOD removal averages >98%. This system is capable of handling surges in wastewater flows and oscillations in nutrient loading and temperature. Nitrogen species are thoroughly oxidized to nitrate in the field unit. Removal rates of fecal and total coliforms average 99.6%. A typical household would require a 3 m^3 biofilter to renovate >1,500 L/day in cold climates and less in warmer areas. Treated water with BOD and TSS typically <1 mg/L could be stored in an ordinary water tank for use within the structure. The unit can operate without a ventilation fan if complete nitrification is not required.

An alternate design for the treatment of grey water is shown on page 24.

This wastewater biofilter design consists of two concentric cylinders topped by a porous media filter. Liquid effluent flows into the bottom of the inner cylinder and is then pumped upwards and then sprayed onto the porous media above it. As the liquid trickles down through the randomly packed media, aerobic Nitrosomonas bacteria living in the bio-film and coating each of the particles convert the ammonia in the wastewater into nitrates. The liquid then drips through the porous media into the outer cylinder where anaerobic Nitrobacter bacteria transform it into nitrogen gas that is vented to the outside air. Such a biofilter is capable of reducing nitrate concentrations in the inlet wastewater by up to a factor of ten.



Alternate design for the treatment of grey water.

This simple and economical system has many attractive features; therefore it can be put forward for further consideration in a LEED certified green building.

It is possible to add an additional treatment stage to clean the purified water outlet still further. A small greenhouse or glazed enclosure can be built to house a biological treatment system. Inside the enclosure, water treatment occurs in a series of linked hemispherical tanks that contain a variety of ecosystems, including bacteria, algae, floating plants, snails, and fish that process the water before it goes through an artificial marsh. An artificial marsh is similar in function to the processes that occur in natural wetlands. Water flows by gravity from one tank to the next. These tanks contain algae, zooplankton, phytoplankton, snails, bloodworms, and specially selected aquatic and non-aquatic plants. The tanks can be aerated to keep bio-solid particles suspended in the water, making them readily available for consumption by organisms and plants. As the wastewater slowly flows from tank to tank, the organic constituents become food to the organisms present in the containers. As it moves up the food chain, much of the organic mass is eventually converted to basic constituents such as carbon dioxide, water, and energy. That portion of the mass that is converted to animal and vegetative growth is periodically harvested and composted.

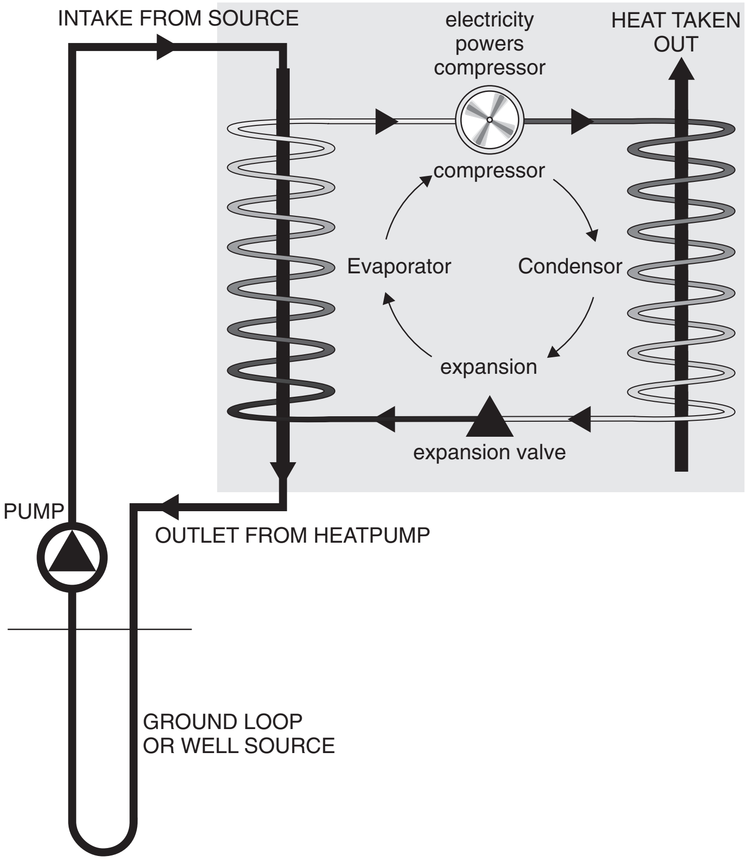
The wastewater drains by gravity from clarifying tanks to a swirl separator that helps remove most of the remaining solids (mostly plant matter). Sludge from this clarifying process can be digested aerobically in an underground sludge tank, thickened, decanted, and then applied to an outdoor reed bed composting system. Both the under drain from the reed beds and decant liquid are returned to the blending tank. The thickened sludge is applied to the reed bed in very thin layers. The reeds serve to further break down sludge anaerobically over a period of weeks, eventually producing a benign and fertile soil amendment.

In the final stage, effluent from the clarifying tanks flows by gravity through a sand filter or micro-screen before flowing into an artificial marsh constructed of gravel. This marsh is planted with a variety of marsh grasses, flowers, and plants. The marsh is a point of denitrification, nutrient uptake, and phosphorus absorption. Effluent can be discharged into rivers, streams, or onto the ground surface depending upon local regulations. In some jurisdictions, effluent is being used for crop irrigation and drinking water for cattle. The effluent can be used for watering lawns, supplying fire hydrants, and for flushing toilets. The final effluent meets the highest standards of wastewater treatment.

The greenhouse/glazed enclosure simply acts as a barrier from the natural environment preventing precipitation from being unnecessarily processed, as well as regulating inside temperatures necessary for living organisms to thrive throughout the year. In this approach to grey water treatment, organic materials in the water are not seen as waste products, but as food that is used by the biological community living within the greenhouse. A schematic of the proposed treatment system is shown below.

Water Heating

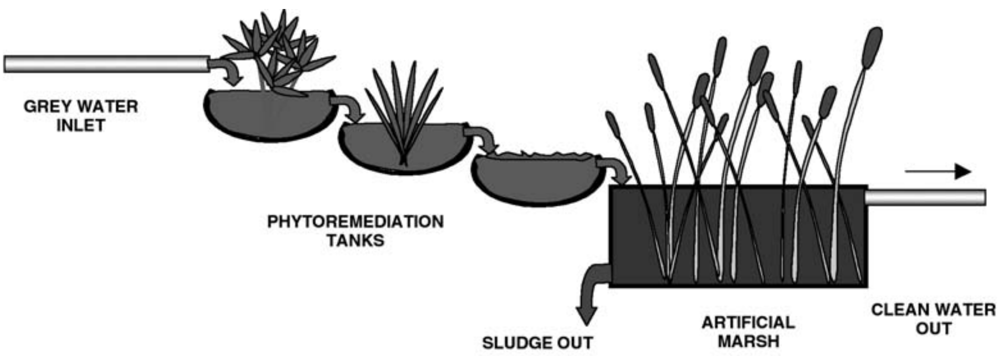
Heat is extracted from laundry and shower water through a heat exchanger on the drain. This served as a preheat for the Domestic Hot Water (DHW) lines. Additional heat as required is provided by an on-demand hot water heater. Water preheat lines also extract heat from the Trombe wall via a heat exchanged during the warmer seasons.



GROUND SOURCE HEAT PUMP SYSTEMS

Ground source or geothermal heat pumps are significantly more efficient than traditional water source heat pump systems. This system works in conjunction with the solar heating to provide all the heating requirements for the prototype. In other words, no fossil fuels are burned to heat the building.

Heat pumps work on a similar principle to domestic refrigerators, extracting heat from one source and transferring it to another. A key ingredient in the heat pump is the refrigerant in its coils, usually Freon, which vaporizes into a gas at a boiling point far lower than the 100°C that water requires to boil. When the refrigerant boils, it changes from a liquid to a gas, absorbing heat from its surroundings. As the refrigerant changes back into liquid form, it gives up its heat to the surrounding atmosphere. This process of transformation from liquid to gas and back again is controlled by an expansion valve and an electric compressor. Heat pumps can be cheaper to operate than other heating systems because, by tapping into free heat in the outdoor air, ground, or water supply, they give back more energy—in the form of heat—than the equivalent amount of electrical energy they consume.



For example, in heating mode, a highly efficient heat pump could extract energy from the earth and transfer it into a building. For every 1 KWh of electrical energy used to drive the heat pump, around 3–4 kWh of thermal energy will be produced. In cooling mode, the heat pump works in reverse, and heat can be extracted from a building and dissipated into the earth.

Geothermal systems use the ground, a pond, or well water to maintain their loop temperatures. As a result, no fossil fuel is expended, significantly reducing the energy use of the system. Loop temperatures can range from 35–100°F. The lower loop temperatures provide more efficient cooling than traditional systems, particularly at partial loads. Because the majority of the operating hours in most domestic and commercial applications are devoted to cooling at part load, the geothermal system will be significantly more efficient. For example, a traditional system maintaining a loop temperature above 60°F might have a performance of 22 EER. A geothermal system can have a performance as high as 36 EER.

Design of Ground Source Heat Pump Systems

Using the ground as a thermal energy source and/or a heat sink for heat pumps has long been recognized to have a number of advantages over the similar use of ambient air. Ground temperatures at about 1 m (3-ft.) depth or lower are much less variable than ambient air temperatures. Further, soil or rock at these depths is usually warmer than ambient air during the coldest winter months and cooler than ambient air during the summer months. This fact leads directly to cooler condensation temperatures (during cooling operation) and warmer evaporating temperatures (during heating) for a heat pump with consequent improved energy efficiency. It also results in increased heating and cooling capacity at extreme temperatures, thereby reducing or eliminating the need for auxiliary heat.

Heat pump systems that make use of the ground in this way are called ground-source or geothermal heat pumps (GHPs). The advantages of GHPs over conventional alternatives make them a very attractive choice for space conditioning and water heating for both residential and commercial/institutional buildings. However, GHPs often have higher first costs than conventional systems making short-term economics unattractive. This disadvantage can be magnified in commercial buildings, many of which have much larger cooling needs than heating needs, especially for buildings located in climates typical of the southern United States. For GHP systems using closed-loop vertical ground heat exchangers, this load imbalance can result in a ground temperature increase over time causing system performance deterioration. Increasing the size of the ground heat exchanger or increasing the distance between adjacent heat exchanger boreholes can postpone the temperature increase problem but will also result in higher system cost. An alternative, lower cost approach for such applications can be the use of a hybrid GHP design. In hybrid GHPs, the ground heat exchanger size is reduced, and an auxiliary heat rejecter (e.g., a cooling tower or some other option) is used to handle the excess heat rejection loads during building cooling operation. The extent to which the ground heat exchanger size can be reduced in a hybrid GHP system will vary with location and climate, but it must be at least large enough to handle the building heating requirements. Hybrid GHPs can also be used for sites where the geological conditions or the available ground surface will not allow a ground heat exchanger large enough for the building cooling loads to be installed.

Technology Description—GHP System Types

There are several types of geothermal heat pump systems that can be used for building space conditioning and water heating. The common denominator is that water source heat pumps exchange heat between indoor air (for space heating or cooling) or water (for heating or chilling water) and a liquid (either water or a water-coolant mixture) flowing in a closed loop. The liquid in the closed loop is "conditioned" by exchanging heat with one or more geothermal heat sources or sinks, such as the ground, groundwater, surface water, wastewater streams, or potable water supplies (where allowed). Figure 1 illustrates the various types of geothermal source/sinks that may be used in GHP systems. Hybrid GHP system designs using outdoor air as a supplement heat sink can be configured with any of these GHP source/sinks. Figure 2 is a schematic illustration of a hybrid GHP using a closed loop vertical ground heat exchanger and a cooling tower as an auxiliary heat rejecter. Figure 3 shows the details of the design of a horizontal ground loop, while Figures 4–8 present various sources of low-grade heat that can be tapped by a GHP system.

The closed loop in a GHP system may serve one or many heat pumps, depending on the application. For example, military family housing might be served with

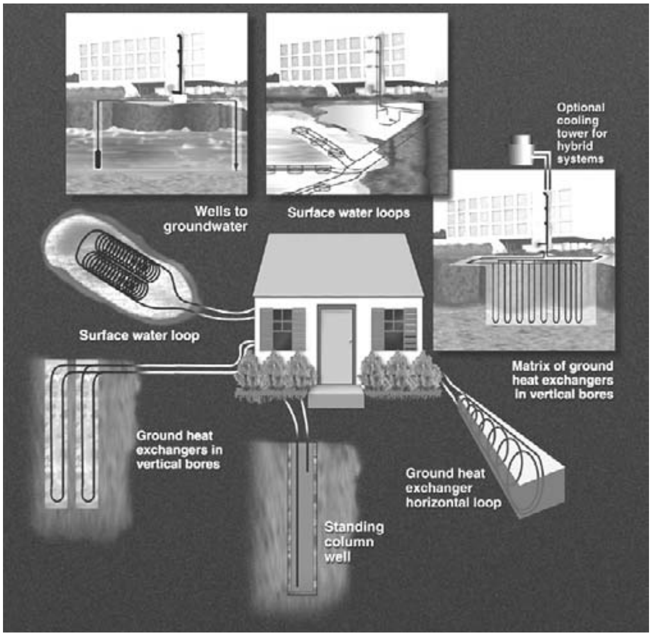


FIGURE 1. Various geothermal source/sinks that can be applied to geothermal heat pump systems in commercial or residential applications.

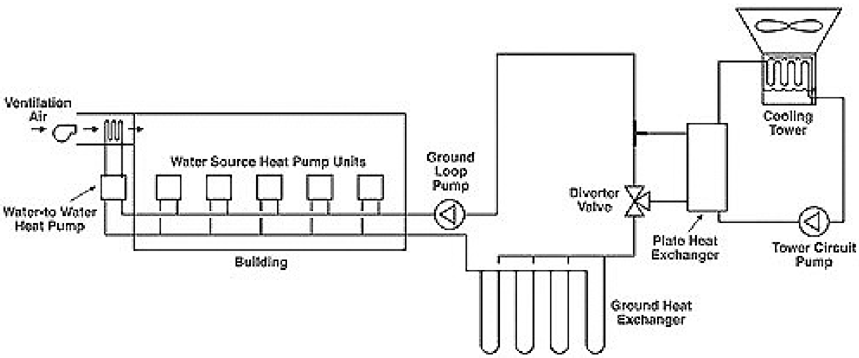
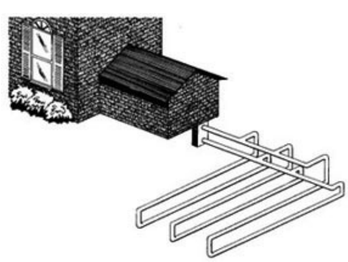


FIGURE 2. Hybrid GHP system schematic—tower isolated from building and ground loop.

systems having one heat pump per living unit, each with its own vertical ground heat exchanger (GHX). Larger facilities might have many heat pumps on a common loop with a central variable-speed pumping station and one large vertical GHX. The schematic in Figure 2 is an example of a large central system type. Individual water source heat pump units provide heating and cooling to each zone within the building. These units are connected to a common interior building pipe loop, which is used as a heat source or sink as needed. Dedicated water-to-water heat pumps may also be connected to the loop to meet building water heating needs or to preheat or cool ventilation air as shown in this example. The building loop is connected

FIGURE 3. Details of the design of a horizontal ground loop.



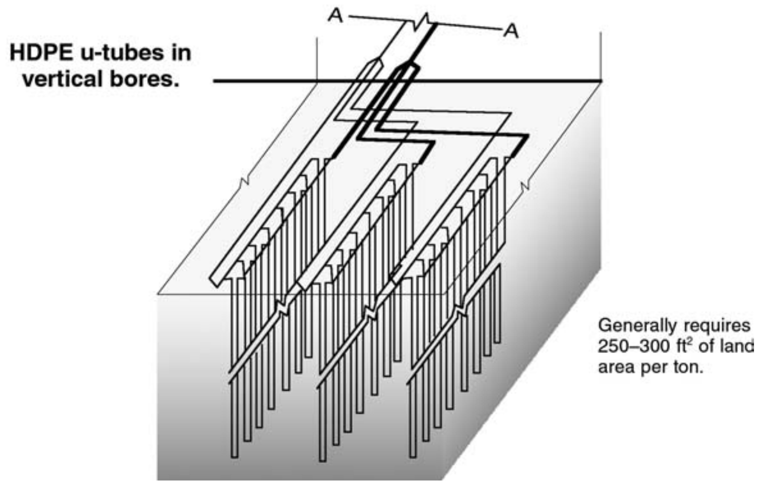


FIGURE 4. Common loop conditioned by a vertical ground heat exchanger.

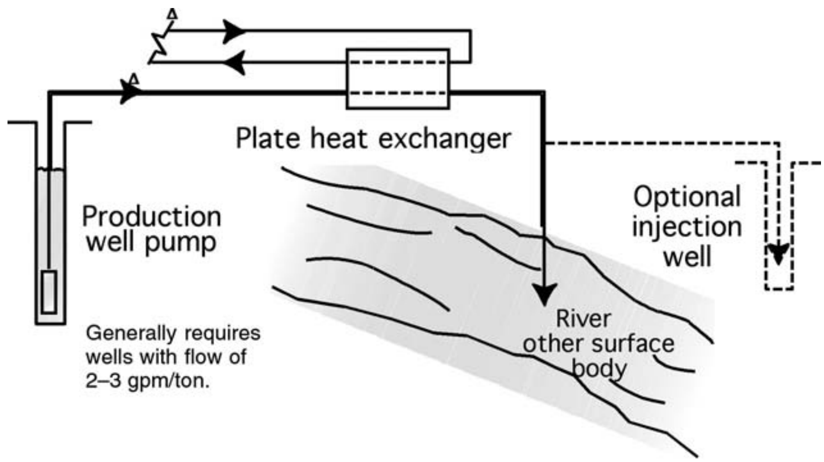


FIGURE 5. Common loop conditioned by a ground water.

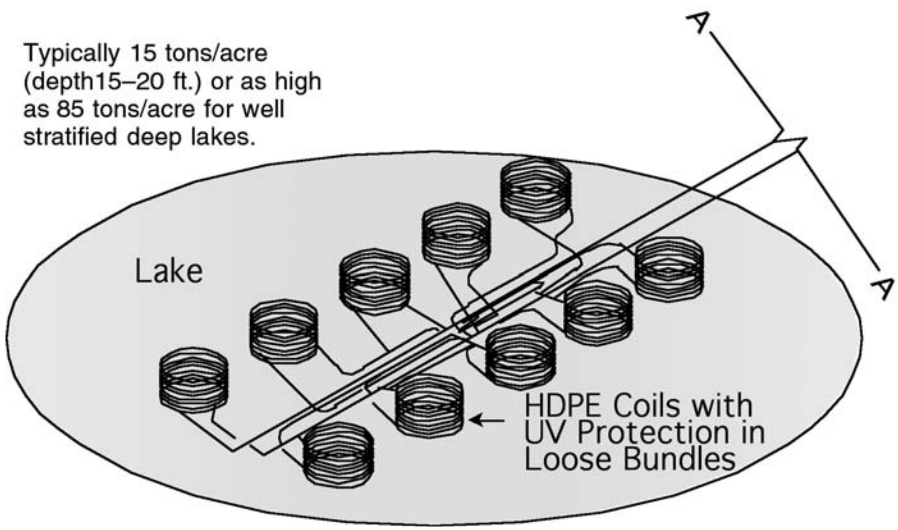


FIGURE 6. Common loop conditioned by a surface water (closed loop).

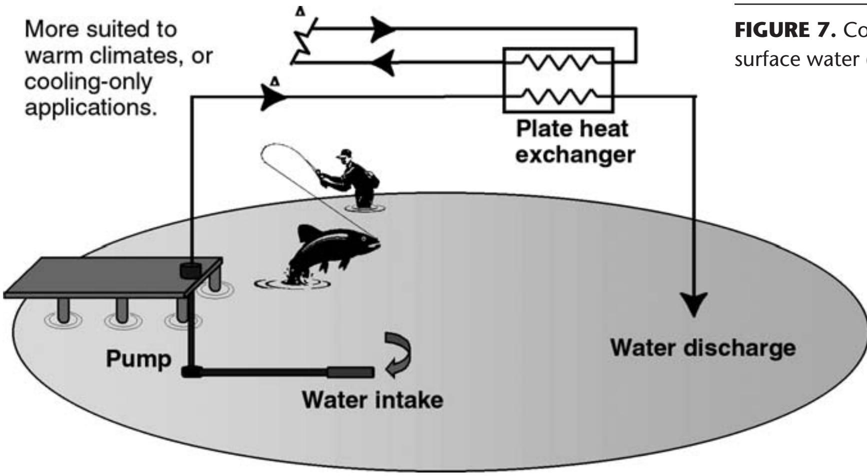


FIGURE 7. Common loop conditioned by a surface water (open loop).

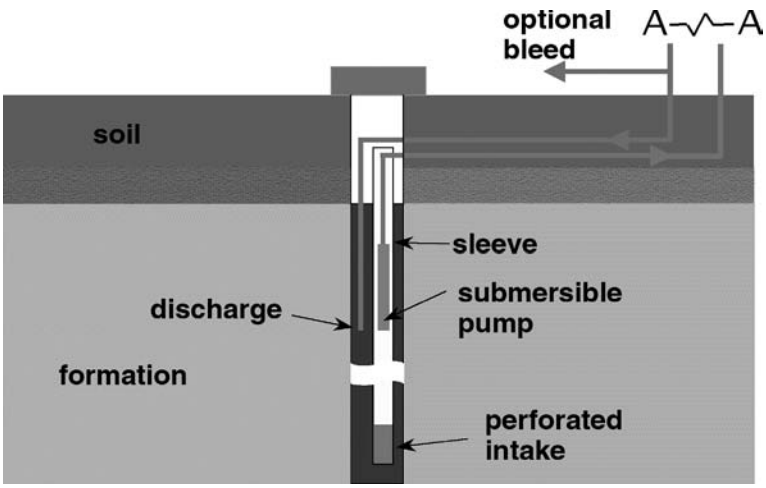


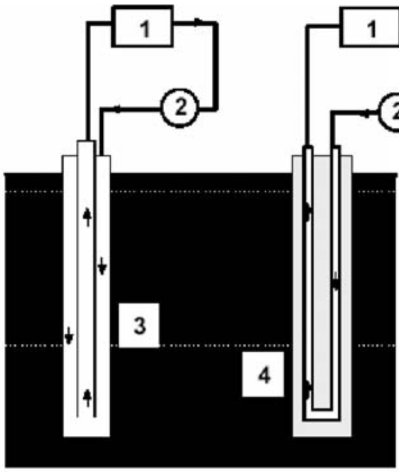
FIGURE 8. Common loop conditioned by standing column well.

to the ground source/sink system (a vertical ground heat exchanger in this case) via a central pumping station. The pumping station may be configured with a few large or several small single-speed pumps in parallel or with variable-speed pumps. Multiple parallel pumps or variable speed pumps offer the possibility of reducing pumping power during periods when building load is lower than the design values. In this hybrid system example, the cooling tower (or other heat rejection unit) is connected in series with the ground heat exchanger and is isolated from the building and ground piping loops with a plate heat exchanger. A wet or evaporative tower is shown in the example, but dry towers may also be used. Systems using dry towers would consume more energy because the tower would have to reject heat to the ambient air dry bulb temperature rather than the lower wet bulb temperature, as is the case with evaporative towers.

Most configurations can be classified as one of the following types.

Closed vertical loop (borehole heat exchanger). Four-inch diameter holes are drilled into the ground to depths of 30–150 m, and piping with U-tube at the bottom is inserted into the holes, which are then grouted. This method is somewhat more expensive than other configurations, but has the advantage of being useful where space is limited or where soil moisture is inadequate at shallow depth. The loop temperature is also more uniform year round at deeper levels, and so less pipe length is required and the performance of the heat pump system is improved (Figure 9).

FIGURE 9. Diagram of borehole heat exchangers: 1) Heat pump unit, 2) Circuit pump, 3) Coaxial-tube BHE, and 4) U-tube BHE.



Closed Vertical Loop. The configuration is like that described above but the loop is built as a coaxial tube. The outside pipe is often made of steel. That kind of borehole heat exchanger can work with a heat pump especially if utilizing old abandoned wells or if the borehole is deeper (Figure 9).

Closed Horizontal Loop. Narrow trenches are dug to a depth of 1.5–3 m, and loops of pipe are placed in the trench, which is then backfilled. A new installation, which requires less trench length, termed the "slinky" after the popular toy, consists of coils of pipe placed in the trench. Trench installations work well where the soil is moist year-round and where enough space is available for their construction.

Open Vertical Loop. Pumps circulate groundwater from one well through the GSHP heat exchanger and either discharge the water on the surface or inject it back into the ground using a second well. There is no change in the quality of groundwater—only heat has been added or extracted. The open loop method has been used successfully where water is plentiful and injection can be readily obtained.

Closed Pond Loop. A closed pipe-loop is submerged in a pond, which is used as a thermal source or sink. This is the least expensive type of installation and works well in areas where the pond does not freeze completely in the winter.

Sizing the Heat Pump

The capacity (power) of a heating system is defined according to the maximum heat demand of a given building. The maximum heat demand, also called the heat load, is calculated for the building according to specific weather conditions and indoor air temperature.

In Canada, the capacity of the heat pump should be designed according to the heat load, in priority to the heating load. It is essential that the design and sizing of the heat pump system are done carefully and should be carried out by an expert. In a new building like the prototype, the architect calculated the heat load according to the characteristics of the building (insulation, area, occupancy, etc.) and local climate conditions.

The heat pumps should be sized in order to have the lowest initial cost and to be working as many hours as possible. The optimum economic size of the heat pump design capacity is normally in the range of 30 to 60% of the maximum heat load of the building. Such a heat pump can cover between 60 and 90% of the annual heat demand. Figure 10 shows schematically the relationship between the heat pump capacity and the building requirements.

As can be seen from Figure 10, an auxiliary heater is used to supplement the heat pump during the colder part of the year. This combination, in which the heat pump is referred as bivalent, is particularly interesting in retrofit situations where the existing heating system can be kept to meet peak demand periods. In new buildings with a high level of insulation and using a low temperature heat distribution system, heat pumps can meet the whole heat load and heating requirement. For safety, a powerful immersion heater can be installed at the inlet of the heat distribution system.

FIGURE 10. Heat pump capacity and building heat requirements in a heat duration diagram. The heat requirements of the building do not include domestic hot water.

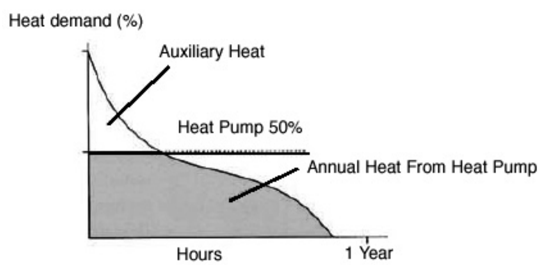


TABLE 1

System	Primary energy efficiency (%)	Specific CO_2 emissions (kg CO_2/kWh heat)
Oil fired boiler	60–65	0.45–0.48
Gas fired boiler	70–80	0.26–0.31
Condensing gas boiler + low temperature system	100	0.21
Electric heating (eff. 40%)[1]	36	0.90
Conventional electricity (eff. 40%)[1] + GSHP	120[2] (160)[3]	0.27 (0.20)
Green electricity (100% eff.) + GSHP	300 (400)	0.00 (0.00)

1. Primary energy efficiency of electricity generation.
2. Value of COP of GSHP is 3.
3. Value of COP of GSHP is 4.

Environmental Benefits of Renewable Heat Pumps

Canadian households emit more than 50 million tonnes of CO_2 per year due to the combustion of fossil fuels for household heating and hot water production. This represents 30% of total CO_2 emissions in Canada. Commercial and public buildings in Canada are responsible for the emission of nearly 9 million tonnes of CO_2 per year (close to 18% of total CO_2 emissions in Canada) due to their energy consumption. About 65% of that energy consumption is for space heating, water heating, and cooling. The main environmental benefit of renewable heat pumps is their ability to reduce the primary energy consumption required for space heating, cooling, and water heating. However, their very high efficiency to produce heat at user's point must be balanced by the power station efficiency at generating the electricity driving a heat pump.

Table 1 compares the primary energy efficiency and carbon dioxide emissions of different heating systems with a renewable heat pump according to the efficiency of electricity generation.

Advantages of heat pump installation include:

- Low operation noise
- Good aesthetics (no chimneys, no cooling towers) and improved room use (no radiators)
- No roof penetrations resulting in reduced potential of leakage and ongoing maintenance
- Increased safety—no combustion or explosive gases within the building
- No local pollution by fuel combustion
- Improved indoor air quality and reduced risk of asthma

CONCLUSION

It is hoped that this exploration of what is possible today changes conventional thinking of what a home could be, not so much in its appearance, but by its metabolism. If we think of our home as a living thing, breathing heating and cooling itself via natural processes, then it becomes an active and symbiotic participant in our world and not a parasitic drain on the finite resources left to us. Indeed we must not forget the Jeffersonian anthem: "The earth belongs in usufruct for the living." By viewing our built environment as a living entity, we insure Jefferson's observation remains true for future generations.

Article co-authored by R. Wayne Guy FRAIC, Principal of Guy Architects, Ltd. and Dr. Paul Tinari P. Eng., Principal of The Pacific Institute for Advanced Studies.

PROTOTYPE HOUSE DESIGN CREDITS

Architecture	R. Wayne Guy, NWTAA/PP,MOAQ, FRAIC., Principal of Guy Architects, Ltd. www.guyarchitects.com
Technical Consultant and Graphics	Dr. Paul Tinari, P. Eng., Principal; The Pacific Institute for Advanced Studies pacific@imag.net
Landscape Architecture	Karen LeGresley Hamre BLA CSLA, Principal Avens Associates, Ltd. avens@ssimicro.com