Compact Exergy Storage Systems

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Abstract - Countries that have cold winters can use the ground to store summer heat for use in the winter but since the temperature of such stored heat is too low for normal heat distribution systems heat pumps are needed to raise the temperature. With ground source heat pump systems the heat pumps operate throughout the day in the winter but if instead they are used in the summer then they need to run only at night when the supply of electricity is plentiful. The result is that the storage system is effectively storing electricity as well as heat. Such combined storage systems can provide for the thermal needs of buildings for space heating and cooling and hot water and they can also provide a means for managing the consumption of electricity on a large scale throughout the year. An effective way to build such stores is to split the storage into two parts: a long term store that uses the ground for storage and a hot water tank that provides for short term storage of heat at a higher temperature. This type of thermal storage can be linked to hydro power storage to shift the grid power supply timing to meet a fluctuating power demand. This both reduces the power demand peaks and enhances the production of electricity, and also results in a compact field of heat exchange boreholes.

Key-Words: exergy, energy, energy storage, heat pump, heat exchanger, solar energy, isothermal, borehole

1 Introduction

A previous paper, *A Dual Function Energy Store* [1], explained how summer heat could be collected and stored in the ground at a relatively high temperature for recovery in the winter for space heating. Such systems can also provide a cold zone in the ground that can be used as a heat sink for air conditioning as well [2], and they can shift the demand for heat pump power away from high power demand periods to low demand periods [3]. The latter feature enables them to function much like electric batteries [4]. These capabilities are useful but in the original concept [5] they operated by trapping heat between three concentric rings of ground heat exchangers so they required many boreholes and the diameter of the outer ring was large, at about 25 metres, which limited their suitability for dense urban sites.

The original design used a hot inner zone that was heated by solar collectors and that was surrounded by an outer zone that accumulated heat from low temperature sources (like the heat extracted from the summer air). The outer zone raised the ground temperature to a value that was high enough to enable the core to reach 60 degrees so that it could provide heat for domestic hot water. The space heating energy was drawn from the middle ring of heat exchangers, augmented by heat drawn from the core as needed on cold days.

A split energy storage system uses the same sources of energy and operates at the same temperatures but it requires far fewer boreholes (typically 8) and they will fit within a 6x6 m area of ground so they are much easier to install. Most of the heat is actually stored outside of the outer ring so the active volume is not really reduced but the boreholes can be much more tightly grouped. The hot core has been replaced by an isothermal heat storage tank. The word "exergy" can be used in place of "energy" because the system does more than just store heat - it also stores exergy [6] since it provides the ability to utilize the stored heat (or cold) for space heating and cooling and for hot water without requiring any power at the time of recovery. Alternatives like ground source heat pumps need power to drive their heat pumps throughout the day but exergy stores draw power only in the middle of the night, when power is cheap and plentiful. They provide a means of tackling two basic issues in the buildings sector - rising global temperatures and rising costs.

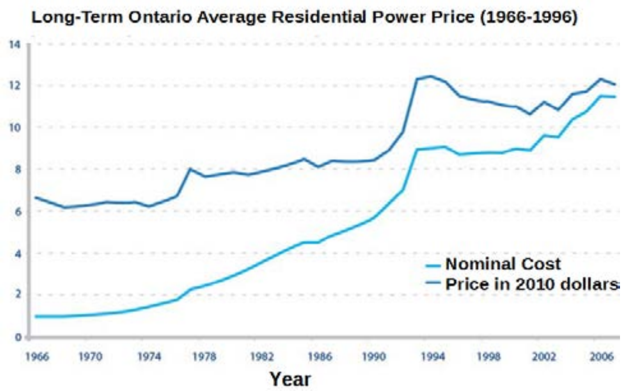

Figure 1 The price of electricity is rising rapidly, and this is a significant deterrent to economic growth.

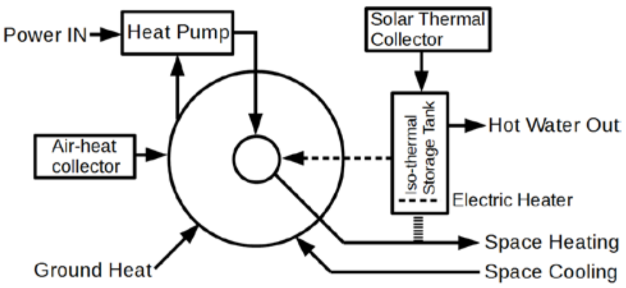

Figure 2 Diagram of a split exergy store.

2 Design

The compact exergy store has six major components, all of which are conventional:

1) An outer ring of heat exchangers - minimum of 3 boreholes (typically 4)
2) An inner ring of heat exchangers - minimum of 1 borehole (typically 4)
3) A heat pump that moves heat from the outer ring to the inner one
4) An air-heat collector that collects heat from the air in the summer
5) A solar thermal collector that collects solar heat throughout the year (optional)
6) An isothermal heat storage tank

There are secondary components such as circulation pumps (powered from a storage battery that is recharged at night), a controllable heat exchanger that transfers excess heat from the isothermal tank to the inner ring and another controllable heat exchanger that draws some heat from the isothermal tank to regulate the temperature of the space heating loop.

In the summer heat is collected during the day from the three low temperature heat sources and is temporarily stored in the ground around the outer boreholes before being pumped into the core at night [7]. The heat pump normally operates from midnight to 6 AM, utilizing the excess electricity that is usually available in that period to pump the heat from the outer ring into the much more compact inner ring, raising the temperature. The heat pump operates for 50 weeks per year, the two week gap being a brief period after the air conditioning season ends that provides for a transition in the storage function. During the first year of operation the heat pump may operate in the daytime to charge up the thermal storage. On nights when the power is needed for other purposes the operation can be skipped providing the annual storage quota is met.

The heat pump extracts heat from the outer ring, chilling it. During the summer enough heat is injected into that ring to maintain its temperature at 4 degrees (close to the boreholes), which is suitable for those boreholes to serve as the heat sink for air conditioning. The heat that is injected into the core takes several months to reach the outer boreholes. The spacing between the boreholes is chosen so that the core heat will just begin to reach the outer holes at the end of the air conditioning season. The heat pump is then switched off for two weeks but the air-heat injection continues so the two heat sources rapidly raise the ground temperature around the outer boreholes to about 18 degrees C. The nighttime operation of the heat pump then resumes, with its dwell time being adjusted to maintain the outer boreholes at 18 degrees until the start of winter. During the fall the heat pump continues to operate at night but now it is drawing heat from ground that is 14 degrees warmer than the summer temperature so the core can be heated to a higher temperature. During this period no energy is being added to the system (apart from some heat from the heat pump) but the exergy of the core is being boosted. It will reach a temperature that is high enough to make it practical to heat the buildings using conventional hydronic or ducted heating without relying on a heat pump.

Through the winter the temperature of the outer ring will gradually fall until it resumes its summer value of 4 degrees. In an area that has a 10 degree ambient ground temperature the result is that the temperature of the outer holes swings between 6 degrees below the ambient temperature and 8 degrees above that temperature so there is no net gain or loss of heat to the surrounding ground. The temperature swing is not quite symmetrical because the dwell time at the higher temperature is relatively short. So long as there is no loss of heat from the outer surface of the storage volume then no energy is lost with such systems. Most other energy storage systems involve conversions of energy from one form to another, such as to chemical form in batteries, so they lose energy in going through two such conversions and they lose more energy during the storage period, but thermal storage is not subject to such losses. There will be small heat losses from the top and bottom of the store but such losses are negligible if the borehole depth is much larger than its diameter. They can also be cancelled out by making the temperature cycle of the outer ring slightly asymmetric so that absorption of ground heat compensates for the end losses.

The storage goes through four phases. In the summer heat is extracted from the local heat sources and pumped into the core. In the fall the heat pump boosts the temperature of the core, increasing its exergy without significantly changing the amount of energy that is being stored. In the winter the heat is extracted from the core but the heat pump continues to draw heat from the outer ring so that the core remains hot while the outer zone cools. In the spring the warm spring air is used to bring the store back to its starting point, ready for another annual cycle to begin.

This year round operation of the heat pump has an important implication for the power grid. The power demand goes through a daily cycle on 365 days of every year. Figure 7 [8] shows a typical example, with the demand falling to a low value at night and then increasing during the day to power the daily activities. In the summer the demand peaks are higher when the air conditioning systems are working harder as shown in Figure 4 [9]. Throughout the year the demand for hot water adds 17 to 19% to the daytime power demand in Ontario [10]. Buildings and communities that employ exergy stores will see higher nighttime power demands and low daytime demands. In the winter there is currently a large increase in the power demand at all times of the day caused by the heating loads. In Canada the annual thermal loads total about 1833 PJ [11] (Residential + Commercial + Institutional) which is much larger than the Canadian total for electricity production, which amounts to 927 PJ. There is thus a very large potential for reducing the day to night demand variations and consequently there is also an important potential for reducing the consumption of fossil fuels for thermal applications.

Where fossil fuels are used for power generation the day to night load variations are a minor consideration because the fuel burn rate can easily be adjusted to match the load. However, in converting to renewable energy sources the problem of matching the supply to the demand becomes a major problem. Reducing the demand swings is a big advantage. Being able to adjust the electricity supply to more closely match the temporal demand is a further advantage. Exergy stores do both. At the same time they are replacing the use of fossil fuels for thermal applications and they are providing the needed storage to cope with both thermal demand variations and electrical demand variations.

During the winter the stored heat is extracted from the core for space heating. The heat pump continues to operate at night, replacing some of the extracted heat with heat being drawn from the outer ring. The heat extraction causes the temperature gradient around the inner boreholes to fall so that any heat that is injected by the heat pump (or the solar collector) will remain physically close to the holes, which means that it can be extracted at a high rate on cold nights and it is not subject to any further recycling through the heat pump. The core is thus acting like a nearly ideal store. It does not lose any energy and it is capable of absorbing and delivering heat at a high power rate. That makes it an excellent candidate for storing energy from other sources, like solar energy or heat that could be produced from surplus electricity. An electric heater in the water tank serves a dual purpose - to keep the hot water at the desired 60 degree C temperature and to provide a means of absorbing any surplus of electricity.

By the arrival of spring the heat from the zone between the two rings will be exhausted and the temperature at the outer boreholes will have fallen back to roughly 4 degrees. That heat deficit needs to be replaced to return to the summer starting point so the heat addition and pumping starts up again. The replacement process uses air-heat that can be supplemented by solar heat, which with an appropriately oriented collector will produce its maximum output in the late winter and early spring.

2 Adding solar thermal energy

Running the heat pump during all four seasons takes its toll on the seasonal Coefficient of Performance (COP) because power is being used in all seasons even though most of the heat is only being delivered during the winter. No energy is actually being lost because there is no annual net flow of heat being lost from the periphery. This all-season power drain is useful in that it leads to the capability to flatten the grid load, but nonetheless it is desirable to minimize the power demand. That can be accomplished by adding solar thermal collectors that inject heat directly into the core so that the need for running the heat pump is reduced. The amount of added solar heat is a design decision. It would be feasible, for example, to add enough solar heat to improve the seasonal COP to a value of 5 or more, but that would entail reducing the power input so the ability of the system to flatten the power demand fluctuations would be compromised. The choice is up to the designer, who can optimize either the COP (which benefits the building owners) or the grid load flattening (which benefits the power generating and distributing organizations). That obviously raises the question of who should build such systems - the building owners or the power companies.

The solar input can be very efficiently exploited in exergy storage systems. At any time of year the solar input is used first for a daily "charge up" of the storage in the isothermal tank to ensure that there will be enough heat available for hot water. In the winter the solar heat tops up the temperature for the space heating that goes to the buildings. On days when there is a surplus of solar energy available the circulation pump of the link to the core is started and runs until the excess heat is transferred into the core. During the critical winter period that heat is very efficiently utilized as explained above and it provides the second function of regulating the space heating loop. During winter the core temperature will drop so the amount of boost that is needed will increase, but the solar input also increases quite sharply through the latter part of the winter so the ability of the isothermal tank to compensate for the temperature drop is enhanced.

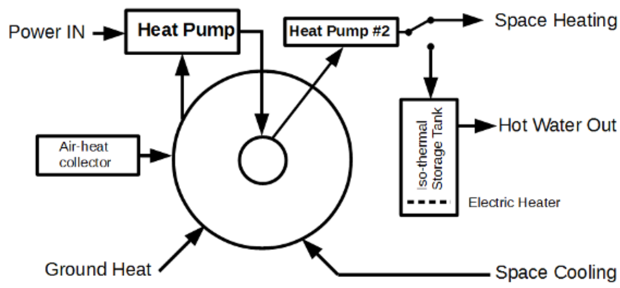

Figure 3 Not all sites are suitable for solar collectors, and in that case this hybrid design can be used.

3 Adding extra energy (plus a hot water backup)

The size of the solar collector in an exergy store is larger than those used in solar hot water systems but since the sun may not shine for quite long periods the backup electric heating is still needed for safety. The electric heating can also serve an important additional function. If we want to use erratic renewable energy sources like hydro, wind, solar PV, etc. then we will need to develop a means of storing their excess output that is produced at times when the grid demand is low. A popular way of doing that is to use electric batteries but such batteries are very expensive, they have a limited lifetime and they lose energy over time and in going through two conversions to different energy forms. Exergy stores can accomplish the same task more efficiently and at a cost that is lower by orders of magnitude.

Let us say that the wind is blowing strongly on a spring day. At that time of year the grid demand is low so any extra electricity that is being produced cannot be used immediately so it needs to be stored. If that extra electricity is fed to the isothermal tank's heater then the energy will be utilized by the tank or fed to the core of the store, where it will be retained until it is needed at a later time. None of the heat will be lost in the interval because there is no net heat outflow through the store's periphery. Eventually all of that heat will be used either for space heating or for hot water. As things stand a large part of our electricity in Canada is used for heating and hot water so every kWh of stored electric-source heat will in time displace the need for a kWh of electricity. The exergy store is performing like a battery, but it is cheaper, more efficient and it has eliminated the need to transmit the electricity at times when the grid is heavily loaded.

Note that exergy stores provide several valuable functions in supporting the electrical grid:

1) they reduce the grid demand by eliminating the use of electricity for thermal applications
2) they shift demand from peak periods to off-peak periods, which reduces the peak demands and hence the capital cost of the generation facilities
3) they eliminate the need to transmit power for thermal applications
4) they increase the generation capacity, for example by enabling us to utilize the spring surge of our rivers
5) they provide a general means of matching grid supply and demand

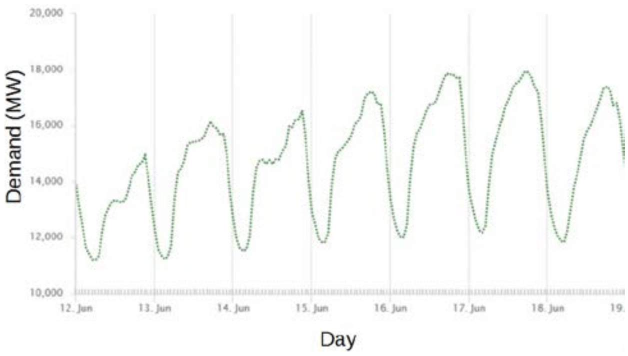

Figure 4 The power demand swings over a wide range from day to night, especially when the weather turns hot as in the above example.

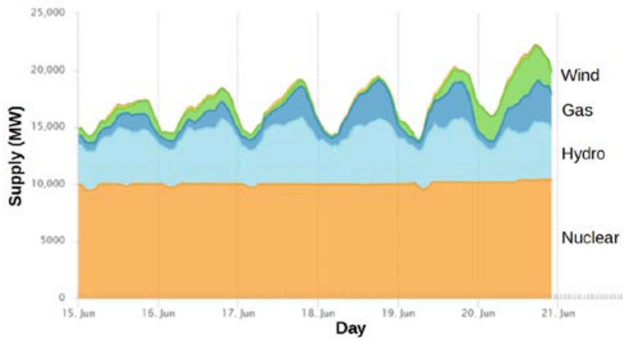

Figure 5 In peak demand periods natural gas generators are used in Ontario [12]. Storage could eliminate the need for using fossil fuels for power and buildings, and would facilitate the use of alternatives like wind turbines.

4 Matching grid supply and demand

This function is not self-evident so it needs to be explained. Exergy stores draw a lot of power during the night. Part of that is power that is used to drive the heat pumps and part is surplus power that we want to store until it is needed. The grid demand during the daytime peak periods is reduced because heating, cooling and hot water are all being supplied from local stored thermal energy. This reduction in the demand difference between night and day reduces the need for the hydro dams and ponds to store the potential energy that drives the daily load fluctuations (Figure 8). However, that potential storage capacity is not lost. It can be re-purposed by adjusting the demand of the exergy stores to make full use of the power storage capacity of the dams/ponds. In Canada it is that hydro pond storage capacity that handles most of our grid demand fluctuations. Canada has very few pumped hydro facilities, attesting to the capacity of this storage mechanism to handle the load variations. Adding exergy stores can both reduce the annual and peak electrical loads, it can also re-purpose the hydro storage capacity to handle either supply or load variations, whatever the cause.

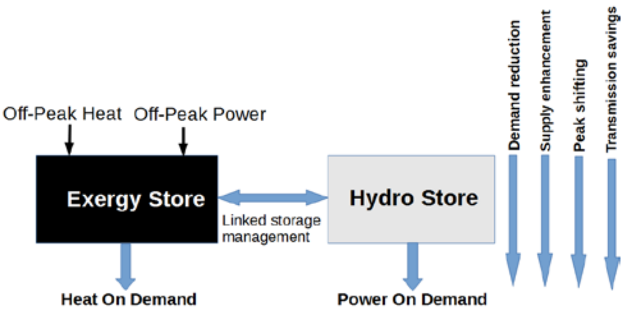

Figure 6 The storage functions of exergy stores and hydro dams can be linked by controlling the grid demand so the exergy stores make it possible to supply both heat and electricity on demand.

In Canada over 59% of our power comes from hydro power [13]. If you put together the five functions listed above then in principle all of Canada's needs for energy for buildings could be met using just two energy sources: local thermal energy sources and hydro power. Such a country-wide system would require a stronger East-West power grid and a resolution as to who should build the exergy stores - the building owners or the power companies.

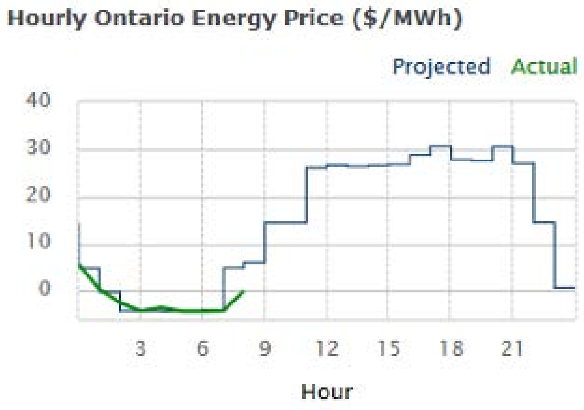

Figure 7 The IESO wholesale price of electricity in Ontario drops to nearly zero (or less) at night so systems that draw power at night can be very economical.

Figure 8 The wide price swings are the consequence of wide demand swings.

5 The isothermal store

The isothermal tank is a water filled tank that receives heat from the solar collector. It has an extraction loop that can transfer excess heat to the exergy store's core as required. When the water temperature exceeds 60 degrees the circulation pump starts and runs for a fixed time, sufficient to bring the tank back to the temperature at which the heat of fusion medium is fully charged. The medium is paraffin wax contained in tubes. The electric heater immersed in the tank serves the dual purpose of preventing the hot water temperature from falling to an unsafe level and of providing a means of absorbing excess grid power.

A pipe passing through the tank provides hot water on an "on-demand" basis. It needs to be long enough (or use fins) to enable input water at 10 degrees C to be quickly heated to at least 40 degrees C. The potable water supply and the hot water in the tank are isolated from each other, apart from the thermal connection.

6 The link to the space heating line

A controllable amount of heat is transferred from the isothermal tank to the space heating line. The link superheats the line fluid and regulates its temperature. The heat flow can be controlled mechanically or via the use of an adjustable flow valve or a variable speed pump. The heat storage capacity of the storage medium is limited, and is much less than the daily mid-winter heating demand so this link only provides a fine adjustment of the temperature. The primary method of ensuring adequate heat flow is to design the system so that the core temperature does not drop much below the 50 degree C design objective. (Conventional heating systems operate at higher temperatures so when an exergy storage system is retrofitted to an older building it may be necessary to modify the building's heat distribution system by increasing the radiator capacity or using underfloor heating.)

7 Example

Table 1 (see Appendix) shows the power consumption for a detached house along with other relevant parameters.

Table 1 shows the actual monthly power consumption (column 1) of a typical detached house in Ottawa. It uses electric baseboard heating, an electric hot water tank and electrically powered air conditioning. Column 2 shows the solar heat contribution that could be expected from a fixed solar collector (at a 60 degree angle) that is 10 m^2 in area and that functions at 50% efficiency, based on the solar insolation data tables for Ottawa published by Natural Resources Canada [14]. Some heat will added by the electric heater (column 3) in the isothermal tank but the amount will be determined by the power supply company in accordance with their need to store excess electricity. In this case a nominal 5% of the annual heating input is assumed except for April and May when the input will be higher because of the spring runoff. In late summer the hydro output is normally at its minimum so it is assumed that the excess hydro power will be minimal in those months. Column 5 shows the energy balance that the house will need from storage from the local thermal sources plus the heat pump's own heat contribution.

In this example the capacity of the system to provide sufficient energy is not in question. Either the air-heat collector or the solar collector could if necessary be sized to provide most of the required energy. The principal design question is whether the heat extraction exchangers can deliver the amounts of heat shown in column 5 after allowing for the contribution of the isothermal tank, which can contribute heat at very high rates but only in a limited quantity per day. Experimental results from the "testbed" system described in reference 1 indicate that if the ground has good thermal conductivity then four extraction exchangers should be sufficient, but more boreholes might be needed if the thermal conductivity is poor.

Based on government reports Canadian homes use 17 to 19% of their energy input for heating hot water, which amounts to 3,519 kWh per year in this case. Since the demand drops to about 28 kWh/day in the months when space heating is not required the non-thermal electricity consumption can be estimated to be about 18 kWh per day, or 6,700 kWh per year. That leaves 20,704 - 6,700 = 14,004 kWh as the thermal energy consumption of the house, of which the solar collector is providing 8,903 kWh. The heat pump must deliver the remaining 5,101 kWh.

The cost of the electricity for the heat pump is almost zero if it is purchased at the night time wholesale price, and it amounts to only about $200 per year if it is paid for at the retail rate. The energy supply savings for a power cost of 20 cents per kWh can therefore be estimated to be 14004 x 0.20 - 200 = $2,601 per year for space heating. The energy supply cost for cooling would drop almost to zero. Against this a homeowner needs to consider the capital cost of building the exergy store.

The question is not so much what that capital cost amounts to as to who should build it. The real economic benefits of such storage systems are realized by the electricity suppliers, not the homeowners. If those suppliers build the stores then the homeowners will save the $2,601 per year without the capital expense.

The electricity demand for thermal applications in this case is 14,004 kWh. However, all of that thermal demand is being met by power drawn during the night, so the reduction in the daytime power demand amounts to about 10,503 kWh (i.e. 75% of 14,004) plus the 1,192 kWh of stored excess electricity for a total of 11,695 kWh, or 56% of the home's current demand. The implication is that the capital cost reductions for generation and transmission facilities would be very large. That suggests that the power companies should pay for the cost of the exergy stores. In that case both the power companies and the consumers stand to save a lot of money and the rising cost of both power and heating could be reversed.

8 Conclusions

The compact borehole fields and the smaller number of ground heat exchangers makes the split energy stores easier to install and cheaper to build than the original design concept.

The economic benefits of such stores primarily accrue to the power companies, not the building owners, so if the power companies build the stores their deployment would occur faster and both parties would gain substantial benefits, including reduced power prices and reduced capital expenditures.

The use of fossil fuels could be reduced or even eliminate for both space heating and for peaking power generation.

Such a GHG-free system would be sustainable for many decades to come.

Hydro stations would be able to generate more electricity and other renewable sources like wind turbines would benefit from the ability to store electricity.

The storage capacity of the hydro stations could be re-deployed by linking their demand controls with those of the exergy stores.

Exergy stores serve two different functions: storing heat (and cold) for thermal applications and storing electricity for the grid. The two functions are inextricably linked - neither works without the other. There is no reasonable upper limit on how much heat could be stored but the amount of electricity that can be stored is inherently less than the amount of heat being stored. Since Canadians need a lot of heat in the winter it follows that there is a potential to also use exergy stores to store a very large amount of electricity, but both parties - heat users and electricity generators - must agree to work cooperatively.

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Appendix

Table 1
Electricity consumption for a detached house

	Daily consumption (kWh/day)	Solar contribution (kWh/day)	Excess hydro electricity added (kWh/day)	Required balance from storage (kWh/day)
Annual avg.	56.7	24.4	3.3	29.0
Jan	98.9	21.0	2.8	75.1
Feb	96.1	28.0	2.8	65.3
Mar	79.8	30.8	2.8	46.2
Apr	72.9	27.2	5.6	40.1
May	43.9	26.3	11.2	6.4
Jun	28.3	26.5	1.8	0
Jul	27.0	27.0	0	0
Aug	33.1	27.2	0	5.9
Sep	29.9	24.8	0	5.1
Oct	41.6	21.7	2.8	17.1
Nov	56.1	15.6	2.8	37.7
Dec	73.1	16.6	2.8	53.7
Annual totals	20,704	8,903	1,192	10,609