Sustainable, Resilient Municipal Energy Systems

Abstract

If municipalities meet much of their own energy needs from local sources of renewable energy they can stop both the upward spiral of energy prices and the dumping of CO_2 into the atmosphere. The most immediate need in Canada is to curtail the use of natural gas. That can be achieved by storing summer heat to replace the use of natural gas for heating buildings. The next step should be to integrate wind, solar and hydro energy systems to provide sustainable and resilient electric power generation.

Energy from the air

The air contains energy in two forms: the kinetic energy that is used for generating power from the wind and thermal energy that can be used for heating applications. Although this conference deals primarily with wind power the thermal energy component is currently a major (but sometimes unappreciated) source of energy, and it has the potential to become the most immediate means of relieving some of the current energy supply and price problems. Substituting heat extracted from the air for heating buildings that presently use combustible fuels eliminates the direct production of CO_2

Renewable energy sources of all types depend on the sun as the fundamental source of energy but they are utilized in different forms: hydro power, wind power, solar thermal, solar voltaic, stored heat, heat extracted directly from the air, etc. Fossil fuels similarly have a common ancestry but they too are used in a variety of forms: coal, oil, natural gas and a wide variety of fuels that have been derived from the raw materials. Just as our economies have evolved to depend on this variety of fossil fuels we now need to adapt to a comparable mix of renewable energy products. We cannot replace fossil fuels with just wind power or direct solar power, we need to utilize all of the renewable energy resources and consider how they should be integrated to create a comprehensive solution that copes with short term, daily and seasonal demand variations.

Municipal power

The topic of this paper is to consider how the various renewable sources can be integrated so that together they meet our energy requirements. The first stumbling block is that except for hydro power the renewable sources need to be consumed physically close to their point of origin. You can transport coal, oil or natural gas but it is much more difficult to transport heat. Wind and solar power generation impose a highly variable load on a transmission grid so the transmission lines must be short. In other words we need to abandon the concept of using central generators feeding distribution grids and instead think in terms of municipalities supplying their own needs. Fossil fuels can be left in the ground until they are needed or can be stored in the distribution pipelines, and they can be converted to electricity according to the current demand so a set of national distribution grids makes sense for fossil fuels, but not for renewable energy (with the notable exception of hydro power).

The second stumbling block is that municipalities, or a least those here in Canada, have not yet recognized that they must participate in much of the planning and supply responsibilities that have heretofore been the responsibility of the senior levels of government.

Sustainability and Resilience

At the present time we are experiencing serious inflation in the costs of all forms of energy that depend on fossil fuels. We know that we are currently burning such fuels at a rate that is well in excess of what the world's atmosphere can handle. We know that the reserves of those fuels cannot continue to provide energy indefinitely. We know that we are increasingly dependent on fuels, like the Canadian tar sands, that are difficult to recover and that pose consequential problems like pollution. Most countries are dependent on other countries for much of their fuel supplies, raising questions of supply and transport reliability. Even Canada is increasingly dependent on imported LNG. Everyone knows about those problems but to date the solutions have mostly been token attempts to link renewable energy systems to the existing supply grids. What we really need to do is to replace some of those central supply systems with municipal energy supply facilities that can efficiently utilize local renewable energy sources and can in the process make the cities more resilient.

Missing components

A familiar argument is made that “renewable energy sources are not capable of replacing the existing fossil fuel and nuclear sources” That is absolutely not true. Simple calculations of the solar energy that is available, plus the kinetic and thermal energy of the air, plus the hydro power that is already in place show that these sources are capable of providing as much the energy as we need and can do it with the required power capacity. However, we have not yet developed an overall plan for the switch from fossil fuels to renewables because we are still missing some of the components that will be needed.

If the maximum capacity of a wind generator field is limited to the peak power demand of the load that it serves then the its potential is compromised. However, if the load is decoupled by adding storage or a complementary energy source the contribution from the wind source can be increased. Typical examples are the use of pumped water storage and the complementary use of hydro power to handle the fluctuations in wind power. Half of Canada's electricity is generated via hydro power so there is inherently a very large potential for this type of complementary generation providing issues like achieving a smooth hand off from one source to the other are solved. Since short term support for wind power does not affect the long term usage pattern of the hydro system such a coupled system does not in principle compromise the capacity of the hydro system. The challenges are how to deal with the large seasonal demand variations, the substantial diurnal variation in demand, and the short term issues entailed in quickly switching from one power source to another.

Solar power has the useful characteristic of providing all of its power in daylight hours, when the power demand is greatest. That suggests that if we add solar power to the wind-hydro combination that the combined system will in general be matched more closely to the demand variations. However, since both the solar and the wind generators are subject to relatively rapid supply fluctuations there is a need for a means of handling the transitions.

An interesting way of providing the transition power would be to use some of the wind generator output to heat a storage medium like common salt to a high temperature. If the solar system is a thermal-solar plant then the heat from the high temperature store can be leaked at the required rate to maintain the temperature of the solar plant's heat storage tank, enabling that generator to operate steadily without sudden interruptions..

It is generally assumed that thermal-solar plants are only suitable for use in hot areas like Arizona or Spain where the brilliant sunlight makes it possible to achieve the high temperatures that are needed to realize high efficiency in the electric power generators. However, in Canada we have the potential for utilizing the energy in a different way. We can use the waste heat from the generators for heating our buildings, so although the electricity generation efficiency may be lower the overall energy efficiency is higher.

Thermal energy from the air

In Canada there are two very strong energy demand peaks, in the winter to meet heating and winter electricity requirements, and in the summer for air conditioning. Wind and hydro energy are not capable of matching supply and demand during those periods, and the solar source is even less capable of contributing to the winter demand, although it is obviously helpful in the summer. If we can find a way to reduce those seasonal peaks then the way is open to use renewable energy as the general solution to our energy needs for buildings. Thermal energy from the air provides that missing link.

We already make very extensive use of thermal energy from the air. Nearly a quarter of the homes built in the United States in recent decades make use of air source heat pumps that extract heat from the air, boost its temperature with a heat pump, and use the energy to heat the homes [(1)]. The heat pumps are reversed in the summer to cool the homes. Canada's winters are too cold to use air source heat pumps in most regions, but we do use the mirror image technology to cool many of the large buildings in Toronto. The Enwave system [(2)] uses cold winter air to air condition the buildings in the summer. The cold winter air over Lake Ontario chills the water surface, and when it reaches 4 degrees C the water becomes denser so it sinks to the bottom of the Lake, where it inherently retains that temperature. This cold water is drawn out of the lake in the summer and is circulated through the downtown Toronto core to provide cooling for the large buildings without any need for heat pumps, so that reduces the power demand.

This ability to seasonally store heat is inherently used in ground source heat pumps. The ground near the surface follows the annual fluctuations in air temperature but as you go further down into the ground that temperature is averaged so that its value is close to the annual average temperature. That heat can be drawn out of the ground via heat exchangers in boreholes that typically go down 100 meters or more. Extracting heat chills the ground around the borehole but after the winter is over the heat is restored, mostly via lateral heat flow from the surrounding ground. That heat is in turn eventually restored by heat flow from the surface. However, this latter restoration process is very slow so the boreholes must be located far apart to avoid long term heat depletion. That limits our ability to use ground source systems in densely populated urban areas. Moreover, it is expensive to drill the boreholes because of the low energy density in the ground. Fortunately, both problems can be solved by simply injecting heat into the ground during the summer. The summer air contains an almost unlimited supply of heat that is at an appropriate temperature to make it possible to use simple heat exchangers to transfer the heat into the ground.

Note that although the heat extraction process and the equipment used are almost identical to that of a ground source heat pump the source of the energy (the air) is completely different. Moreover there are substantial differences in the construction costs, the operating costs and in the functionality of the air source systems (called Atmospheric Energy or AE systems to distinguish them from the air source systems that do not require storage [(3)]). These differences make it possible to employ AE systems on a very large scale so it is worth explaining their basic design.

Atmospheric Energy (AE) systems

Although Atmospheric Energy systems do not produce any electricity at all, they do provide a method for heating and cooling buildings that is generally applicable in all of the densely populated parts of a cold country like Canada. In doing so they could nearly eliminate the summer power demand peak and eliminate the use of combustible fuels for heating, and could modestly reduce the winter power demand peak as well. This peak flattening makes it much more practical to employ other renewable energy sources like wind, solar and hydro as general replacements for fossil fuels.

The new element is the ability to collect heat from the air and inject that heat into the ground. An air to fluid heat exchanger is used to extract heat from the air, which is at a substantially higher temperature than the ground throughout the summer. The heat exchange with the ground uses a ground heat exchanger that is almost the same as that normally used for ground source heat pumps. The differences are that the AE ground heat exchanger has more tubes, is designed to greatly reduce the thermal short circuit between the warm and cold pipes, and it creates a vertical temperature gradient in the ground. The vertical temperature gradient ensures that the temperature differential along the exchanger remains relatively constant, ensuring efficient heat exchange.

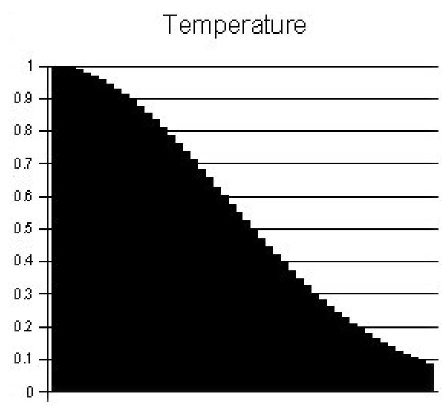

Figure 1 *Calculated temperature vs. distance from the borehole six months after the heat has been injected into the ground. Most of the heat remains within a distance of several meters from the injection point although the maximum temperature at the borehole has dropped substantially.*

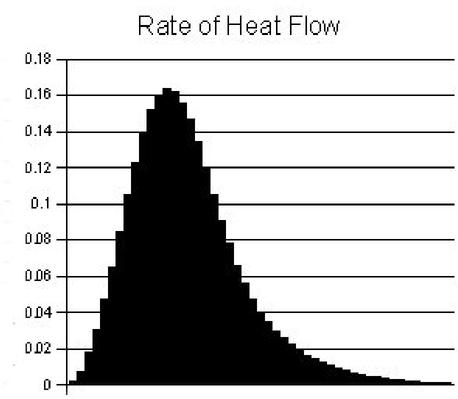

Figure 2 *Calculated rate of heat flow vs. distance from the borehole. For the central boreholes the heat is flowing away from the boreholes but for the outer boreholes as heat is extracted the flow direction is towards those boreholes. When these peaks overlap in the winter the primary heat flow is out of the central (warm) area to the extraction boreholes.*

When you inject heat into the ground it spreads out and the temperature at the injection site falls fairly quickly. However, the injected heat does not move very far Figure 1 shows the temperature profile about six months after injection, starting at the borehole and for a distance of about 10 metres. Figure 2 shows the calculated rate of heat flow over the same distance. The linear velocity of the heat flow becomes progressively slower as time passes so that over a six month period the heat is contained close to the injection point(s).

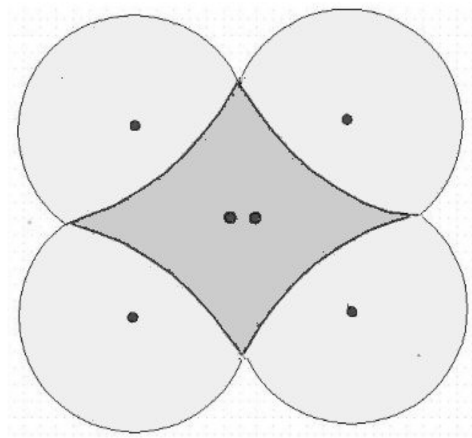

Figure 3 *Plan view of an AE heat storage field. Heat is injected into the two central boreholes and is extracted from the four outer boreholes. The central area is warm but the four outer areas (light grey) are chilled during the winter because of the extraction of heat. The field as a whole contains much more energy than the field of an equivalent GSHP .*

The heat is recovered by surrounding the warmed volume by a set of extraction boreholes as shown in Figure 3. (The number of boreholes is optional). Initially the extraction boreholes function like ordinary ground source heat pump boreholes, with surrounding thermal wells that are below the ambient ground temperature. These wells grow in diameter as heat is extracted, until a point is reached at which their heat inflow peaks coincide with the outflow peak from the central area. At that point the thermal wells will stop growing and the isotherm graph will remain constant as shown in Figure 3, but with a falling temperature in the central area as the heat is drained. During exceptionally cold periods heat can be extracted directly from the warm central area, which provides both a warmer supply and an increase in the heat exchange capacity because of the greater number of extraction tubes. Consequently AE systems do not require backup power from an alternative energy source during extremely cold periods. This, together with the higher coefficient of performance (COP) afforded by a using a heat source that is at a higher temperature, means that the seasonal COP is substantially higher than that for a ground source heat pump, resulting in lower operating costs. The primary factor that determines the capital cost of ground heat systems is the cost of drilling the boreholes, so the comparatively short boreholes needed for AE systems cuts that cost in half.

Many homes fall in between the two extremes - where conventional air-source heat pumps can be used (southern US) and ground storage is needed (Canada). In these in-between areas an AE system can employ a dual mode, operating like a conventional air-source heat pump when the air temperature is moderate and switching to ground heat only on particularly cold days. That reduces the capacity requirement for the ground heat store, thus reducing the borehole length and the capital cost.

Cooling

Air conditioning can be provided by reversing the heat pump so that the building becomes the source of heat and the ground or the air becomes the sink into which the heat is deposited. A different approach can be employed in areas of Canada that have both cold winters and hot summers. Because of the cold winters the extraction wells are chilled to the point where they are still cold during the hot summer months and this cold can be used to air condition the homes without the need of operating the heat pump. The use of four extraction wells facilitates this mode of operation by connecting the cold extraction exchangers in series to maximize the cooling of the exchange fluid. This is particularly useful where the annual heat load is much larger than the cooling load. If that condition is not met then direct cooling can be used in the early summer and heat pump cooling can be employed in late summer.

Energy demands in the Canadian residential sector

In 2005 the shares of the Canadian residential energy demand by source of energy were: (4)

Natural Gas	**46.1%**
Electricity	**38.8%**
Wood	**7.6%**
Heating oil	**6.6%**

Part of the electricity was used for residential heating in 22% of the homes. If those homes used AE systems operating with a COP of 4.0 their share of the power load would drop by 16.5% but on the other hand if the homes using combustible fuels switched to AE systems their demand for electricity would increase by 16.9% after adjusting for the use of direct cooling (2.6%). At this COP the adoption of AE systems would have very little net effect on electricity requirements but as the COP increases with the future adoption of more efficient heat pumps there would be a significant reduction in the winter peak load and a further reduction in the summer elecricity load.

The energy industry consumes a lot of energy for purposes other than production, including the grid losses and transportation consumption. If municipalities used renewable energy sources such as AE systems and locally generated wind and solar power then that secondary consumption could be substantially reduced, but the amount of this secondary consumption is difficult to calculate.

In 2005 the residential emissions of CO_2 were: (5)

Space heating	**57.8%**
Water heating	**17.7%**
Cooling	**2.9%**

The adoption of AE systems could reduce these contributions to zero. The total reduction in CO_2 attributable to the conversion of these applications would thus be 78.4%.

Including all sectors the total consumptions for electricity and natural gas in 2005 were: (6)

Electricity	**1,925 petajoules**
Natural Gas	**2,070 petajoules**

The all-sector totals for carbon dioxide were:

Electricity	**113.5 million tonnes of CO_2**
Natural Gas	**102.8 million tonnes of CO_2**

The predominant source of CO_2 in electricity generation arises from the use of coal, which accounted for 96.6 million tonnes of CO_2 in 2005. For comparison the amount of CO_2 from the use of gasoline in cars was 99.7 million tonnes of CO_2

Stopping the spiral

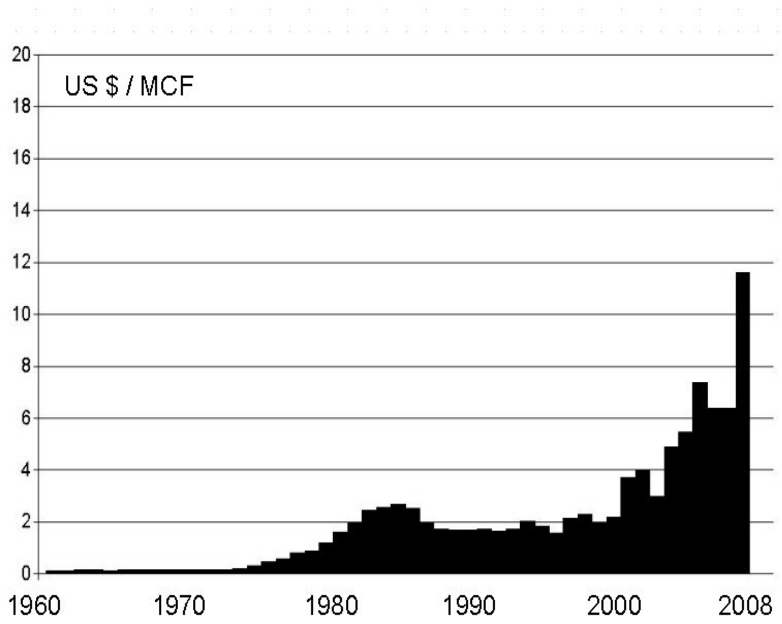

Figure 4 *Price of natural gas in US $ / MCF from 1960 to the present. Data source - US Department of Energy, Energy Information Administration*

The price of natural gas at the wellhead has doubled in the past year and that rapid price rise is expected to continue. In contrast, the price of electricity is expected to remain stable. However, that prediction assumes that we will continue to use natural gas for heating. The problem with that assumption is that once the cost of heating with natural gas exceeds the cost of heating with electricity there will be an almost instantaneous conversion from natural gas to electricity for home heating because it is so easy to add a heating coil to a furnace or plug in an electric heater. Once that happens the demand for electricity will abruptly increase, creating a severe shortage because there is no way to quickly increase the generation and transmission capacities. The inevitable result will be that the price of electricity will also rise dramatically, joining fossil fuels in an upwards spiral.

To stop the spiral we need to curtail the consumption of natural gas, and we need to do that almost immediately. In Canada it is not feasible to avoid heating our homes in the winter but if we pump 1000 petajoules of summer heat into the ground via AE systems the effect is almost the same as adding 1000 petajoules of energy in electric or natural gas forms. That would relieve the supply and price pressures on both natural gas and electricity and buy us some time to deal with the issues of the transportation and electricity supply sectors.

Wind power and stored heat provide energy in the winter. Solar generation and hydro systems tend to provide more energy in the summer. If the four sources are integrated into a system designed to use the appropriate source of energy at the appropriate time then together they can meet most of the energy requirements of a northern country like Canada. Municipal, industrial and agricultural waste can provide a significant contribution that is also renewable, even though it relies on combustion. That source would be particularly useful if it converts the waste to a liquid or gaseous fuel that can be stored to help deal with seasonal or short term supply deficiencies. A system that combines all of those renewable energy sources will generate more electrical power than is needed in the summer, but that is when the US need is greatest so the surplus electricity could be exported to the US.

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