

NYSERDA PON 1200:

**Evaluation of a Pumped Storage Facility Operating Between Lake Erie and Lake Ontario**

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## Executive Summary

This proposal aims to evaluate the largest potential pumped storage opportunity anywhere in North America: the Lake Erie/Lake Ontario System<sup>1</sup>. Even though the most likely site for the actual pumping/turbine facilities is on the Isthmus of Niagara between the lakes (and therefore on Canadian territory), the proposed project would create major economic and system stability benefits for the entire region, including New York. Energy storage is critical to make wind, solar, or tidal power on a large scale practical. Pumped storage is the most economical and reliable way to store electricity either for load leveling or economic dispatch, but it has been difficult to site pumped storage facilities due to environmental concerns. The proposed Isthmus of Niagara project does not require that any dry land needs be flooded (except for minor canal surface area) to implement the project, and so would have much less environmental impact than a comparable project based on new reservoirs (except of course for pumped storage schemes with one reservoir underground).

There is a rapidly evolving consensus that the power grid must be reinforced and expanded to make large scale green energy development practical. What we are proposing is in essence an energy storage scheme that is the same order of magnitude as the next generation of HVDC power lines, capable of providing enough storage capacity to harmonize the available power from wind, tidal, and solar sources with power demand in a large portion of the US and Canada within 1600 kilometers of Niagara. The average 99.4 meter difference of elevation between Lake Erie and Lake Ontario combined with their large surface area could provide up to 1300 gigawatt-hours (GWh) of stored energy output (at 70% overall efficiency) if the level in Lake Ontario is allowed to vary by 30 cm during a charge/discharge cycle (less than the typical seasonal variation of Lake Ontario's level, which is about 45 cm). We propose to access this massive 1300 GWh storage potential via a 10 GW pumped storage facility. Although it would be a massive engineering project to realize the storage potential of these lakes, the benefits for not having to purchase the land, create the reservoirs, and flood dry land for the pumped storage project are very large advantages of the scheme. The proposed facility would be able to deal with peak demand or low wind periods lasting for a week.

It is clear that development of a pumped storage facility between Lake Erie and Lake Ontario would involve international agreements between the US and Canada. There are already numerous examples of cooperative agreements, contracts, and treaties between the US and Canada in the area of regulation of water and hydropower involving the Great Lakes, Niagara River, Saint Lawrence River, and Columbia River, notably the 2005 Great Lakes-Saint Lawrence River Basin Sustainable Water Resources Agreement, and the 1961 Columbia River Treaty. The International Joint Commission is formally tasked with regulation of Great Lakes water, but a project of this magnitude would probably require approval at the highest levels of the federal governments of Canada and the US. Since the proposed project would not remove water from the drainage basin of the Great Lakes, it does not conflict with the cited Water Resources Agreement, but will require an understanding between all states and provinces bordering on either Lake Erie or Lake Ontario, and the Canadian and US governments.

The project principle investigator will be the author, Roger Faulkner, president of Rethink Technologies, Inc. and an experienced research scientist and inventor. I have also served as a Public Intervenor in the Advance Plan 6 Electric Utility regulatory hearings before the Wisconsin PSC in 1991, so I have an awareness of how major new projects are approved. The project team for the proposed study includes several consultants with relevant specialized expertise. Our lead electrical engineer is Professor Shephard Salon of Rensselaer Polytechnic Institute (RPI); he has considerable expertise in pumped storage systems and integration of these with the grid. Professor Joe Chow, also an EE from RPI, will help with issues of integration of the proposed facility into the grid. Professor Joseph Atkinson, who is a professor of civil engineering and Director of the Great Lakes Program at SUNY Buffalo, will consult on the details of the canal structures bringing water to the proposed turbine/pumping facilities. Professor Atkinson will also provide preliminary feedback on the likely effects of the pumped storage facility on the lake environments (thermal stratification, oxygenation levels for example). Professor Keith Tinkler is the Chairman of the Earth Sciences Department of Brock University, which is located very near the most likely route for the hydraulic canals that would be required for the pumped storage facility. Professor Tinkler will provide useful information in re route planning and the local geology.

**Project Benefits**

I presume that anyone reading this document already understands the important role of pumped storage for system stability and economic dispatch. Pumped storage can also provide real time load leveling, and even load following. I propose installing water turbines of several sizes that can hit any desired power level from the lowest relevant power step for system stability up to the maximum capacity (10 GW in generation mode, 14.3 GW in pumping mode) in steps that can be as small as the smallest step. If the smallest relevant step is 1.0 MW (.001 GW), there could be turbines with the following capacities: 1,2,4,8,16,32,64,128,256,512 MW. If however, the 64 MW turbine (for example) was the most cost effective design, then that would be the largest turbine installed, and there would be a lot of them (~157). The capacities of these turbines are like a binary number, allowing any output between 1.0 to 1023 MW to be hit within one MW. This sequence of doubling capacities should go up to the most economically efficient turbine size, which would then be repeated enough times to reach the full 10 GW capacity. For this system to be reliable, there would have to be at least two turbines of each size, to allow for accidental or regular maintenance outages. This system can follow load very closely while running all the turbines at their optimum water throughput for highest efficiency.

It is my belief that the major reason for NYSERDA PON 1200 is to find an alternative technology to pumped storage, because it has proved so very difficult to site new pumped storage capacity in New York. NYSERDA is supporting things like development of advanced batteries, flywheels, supercapacitors and compressed air storage as alternatives to pumped storage not because these technologies are economically superior, but because New York has to find alternatives to pumped storage due to environmental and political concerns. In the most general sense, PON 1200 is seeking innovation and “out of the box” thinking on electrical energy storage, and the proposed Niagara Pumped Storage Project is responsive to that, even though the technologies that will be deployed are quite mature.

**Appendix: Detailed Technical Discussion**

This section describes the project in more detail. Much of the text in prior sections was excerpted from the below.

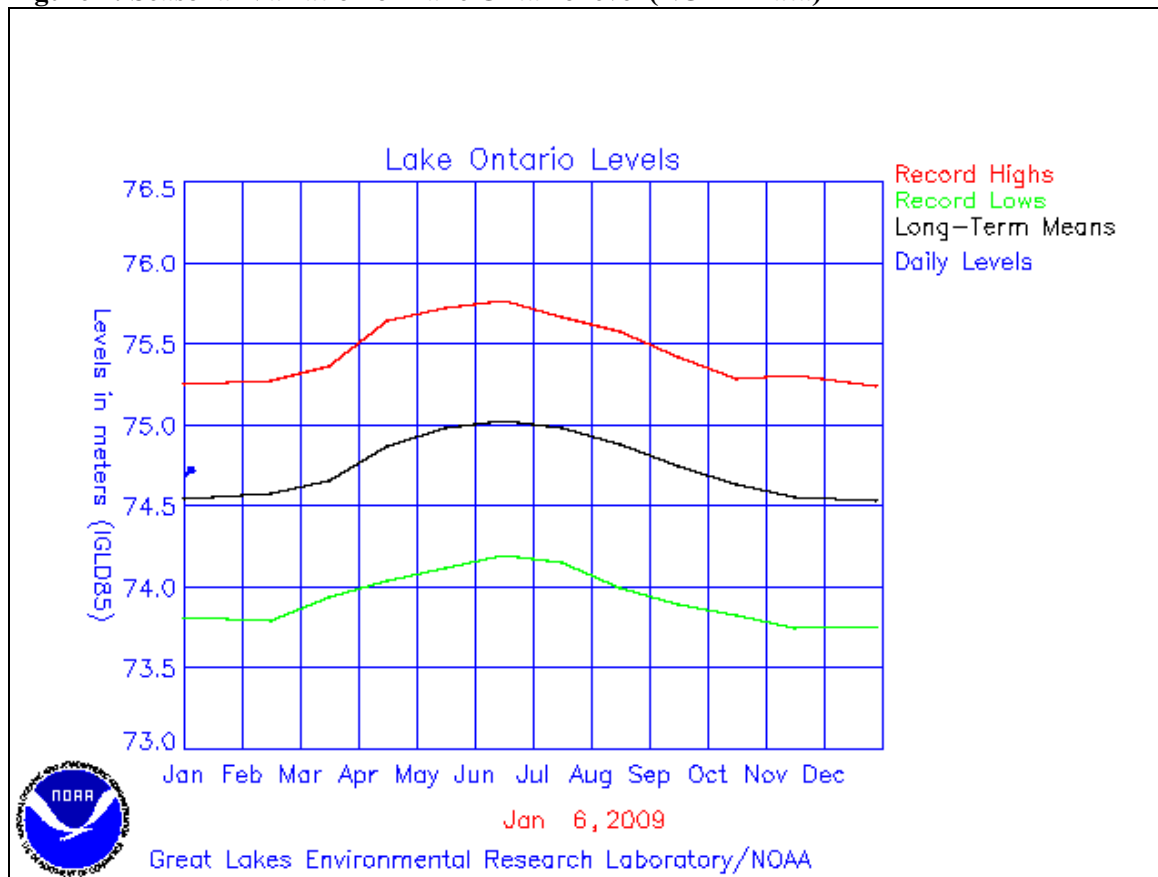
Major advances in transporting electricity on a continental scale via high voltage DC (HVDC) transmission lines (especially high capacity underground lines) could make it practical for wind and solar energy to make a large contribution to our energy economy, in the sense that when green energy is available, fossil fuel plants can be taken offline (saving fossil fuel and reducing carbon emissions). Note though, that wind and solar are not reliable nor dispatchable (because of variable weather), and so can only displace generating capacity (and therefore save on capital cost, not just operating cost) if wind and solar generation are combined with large scale energy storage. Electrical energy storage will be a critical part of any green energy solution that enables non-dispatchable energy sources like wind and solar to make large contributions to the North American energy economy. Energy storage also increases the value of baseload energy sources, like nuclear and run-of-river hydropower. In principle, the storage could be either distributed (for example, by accessing millions of consumer-owned electric car batteries), or based on large utility-owned facilities such as pumped storage facilities<sup>4, 5</sup>. In any case, it is clear that the grid must evolve towards greater utilization of dispatchable energy demand and storage if the full potential of wind, tidal, and solar electricity is to be realized.

This proposal focuses on evaluating the largest potential pumped storage opportunity anywhere in North America: the Lake Erie/Lake Ontario System<sup>6</sup>. Even though the most likely site for the actual pumped storage facilities is on the Isthmus of Niagara (and therefore on Canadian territory), the proposed project would create major economic and system stability benefits for New York. This is especially true in light of the historic difficulty in siting any new hydroelectric generation or pumped storage facility in New York, if it involves flooding a valley (as is usually the case). New York State withdrew in 1994 from a contract to purchase hydroelectricity from a string of proposed new dams on the Great Whale River in Quebec, based on environmental concerns (the project was cancelled shortly afterwards, but is now being considered again). Also, a proposed pumped storage facility at Indian Lake in the Adirondacks was also unsuccessful based on concerns regarding the flooding of a mountain valley. This experience and history essentially rules out any new large hydroelectric facility involving new surface reservoirs, or which floods any new surface areas not previously flooded, including both dams and pumped storage facilities, whether built in New York, or built elsewhere but supported in any way by purchase of electricity by New York. This ethic makes it very difficult to develop pumped storage in the conventional way, even though a high capacity of pumped storage seems to be critical to make wind power on a large scale practical. The proposed Isthmus of Niagara project is especially notable in that no new dry land needs be flooded (except for a few kilometers of canal surface area) to implement the project, yet it would have immense storage potential (about 1300 gigawatt-hours (GWh)). Also, unlike typical pumped storage systems, the 30-cm swing of lake level would not seriously impact the recreational nor the commercial usefulness of the lakes; it would be as if the lakes began to experience a regular tide, which would never be more than a foot.

There is a rapidly evolving consensus that the power grid must be reinforced and expanded to make large scale wind and solar power development practical. For reasons that are familiar to power system designers and engineers, any type of power line capable of moving economically significant amounts of power (more than 50 gigawatts, GW) of electric power coast-to-coast in North America (or even from the Great Plains to New York) would necessarily be a high voltage DC (HVDC) power line. It would also need to be redundant, because of reliability concerns. (We get into more detail on these subjects in our separate proposal in response to NYSERDA PON 1208 on power transmission.) In order to be politically feasible, such large power lines would need to be sited underground; thus the term electric pipeline, or “elpipe,” which we will describe in PON 1208. Pipelines are viewed differently than overhead power lines, and usually do not provoke the magnitude of political opposition that typically arises in response to any new overhead power line proposal in North America or Europe. What we are proposing is in essence an energy storage scheme that is the same order of magnitude as a practical coast-to-coast HVDC power line, capable of providing enough storage capacity to harmonize the available power from wind, tidal, and solar energy with power demand in a large portion of the US and Canada.

The availability of adequate energy storage would make it possible for wind and solar power to contribute a large fraction of total energy needs without negatively impacting system stability. The largest feasible pumped storage project in North America would use Lake Erie (as the elevated reservoir) and Lake Ontario (as the lower reservoir). The average 99.4 meter difference of elevation between these two great lakes combined with their large surface area could potentially provide vast pumped energy storage capacity, up to 1300 gigawatt-hours (GWh) of energy output (at 87% generation efficiency) if the lake level in Lake Ontario is allowed to vary by 30 cm during a charge/discharge cycle (less than the typical seasonal variation of Lake Ontario's level, which is about 45 cm; See Figure 1). This is consistent with the assumption that overall energy storage efficiency of 70% can be attained (86.9% efficiency in generation mode, 85.5% efficiency in pumping mode); 75% or greater efficiency has been attained in some previous pumped storage projects. (The 70% efficiency scenario allows for a 2.5% head loss for viscous dissipation in transporting the water the approximately 35 kilometers to or between the turbine/pump motor/generators, each way, and will be refined during the course of the project by more detailed modeling.)

This storage potential (1300 GWh) is of the same order of magnitude as the installed energy storage capacity of all other pumped storage projects in the world, and although it would be a massive engineering project to realize the storage potential of these lakes, the cost savings and environmental benefits for not having to purchase the land and create the reservoirs per se for the pumped storage project is also very large. (For comparison, the largest existing pumped storage facility in the world is the Guangzhou Pumped Storage Project, which has 14.4 GW-hours of storage capacity.) Development of the enormous potential storage capacity between these two natural reservoirs would make it possible for wind and tidal energy to provide a large fraction of the electrical energy demand of the US and Canada. (It has often been noted that the North American Midwest is the "Saudi Arabia of wind energy," and it could similarly be said that Hudson's Bay is the Saudi Arabia of tidal energy, but to fully utilize this potential, it is essential to provide massive energy storage capacity.) In general, the two main functions of the proposed pumped storage facility would be load leveling and economic dispatch (in which baseload power plants such as run-of-river hydropower and nuclear power plants can store power at night for use during the day, when demand (and value of the electricity) is higher.

**Figure 1: Seasonal Variation of Lake Ontario level (NOAA Data)**

One of the most appealing aspects of the proposed pumped storage project is that there is really no new or in any way unproven technology required. This is simply a massive engineering project, with well-defined goals and methodology. Therefore, low-risk assessments can be made of the cost and energy performance. To fully utilize the energy storage potential of these two great lakes could entail multiple facilities or one single massive interconnection; we have considered both as potential approaches. In terms of detailed calculations we will focus on canal-based designs that involve construction of a power canal that can have either one drop through turbines or several drops. In principle, if a canal with several drops is constructed, it could also have locks and double as both a navigational canal and a power canal for optimized low-head turbines.

In any potential system to harvest the gravitational potential energy of Lake Erie water as it drops down to the level of Lake Ontario, it is possible to either use one pressure drop through one set of turbines or multiple pressure drops through multiple sets of turbines. If economic efficiency of the turbines per se is the primary consideration, then one would install turbines that operate at the full available pressure drop (~99 meter head), but there are potentially reasons to have multiple steps. One possible reason to have multiple steps is to combine the function of hydraulic energy storage with a navigational canal. Another has to do with safety. Another has to do with minimizing the length of feed water pipes connecting the turbines to the power canals (if the canals have modest differences in height, they can safely be brought very near to each other, which minimizes energy losses in the feed water pipes).

Until recently, there was a strong interest in expanding the Welland Canal, so that larger ships could pass through the canal; for the moment, that possibility has been set aside, but in principle it might be revived. It is possible to combine a power generation canal with a navigational canal; indeed the present Welland Canal does generate some power with low-head turbines. There is no fundamental efficiency advantage of one 99-meter head turbine over three 33-meter turbines or eight 11-meter turbines<sup>7</sup>. The multiple turbine options would

probably be more expensive, but having multiple steps might make the canal system per se less expensive or easier to construct. In particular, in a power canal with multiple steps, it would be possible to bring the two canals quite close to each other at each step, which will minimize the cost of the penstock structures linking the turbines to each canal. It is also difficult to anticipate the possible cost effects of manufacturing of a large number of identical low-head turbines. One aspect of the proposed project will be to evaluate both one-step (i.e., one single pressure drop between a high canal and a low canal) and a pumped storage system with multiple steps between canals at different levels. (Making all the steps the same height is expected to lead to economies based on standardization of the turbines.)

The optimum number of pressure steps in taking the water from Lake Erie down to Lake Ontario in a mixed-use canal would depend mostly on the shipping considerations: how high should the locks be to optimize cost efficiency of the system of locks for moving ships from one Great Lake to the next. We have one vital piece of evidence in this regard: The existing Welland canal has seven lift locks (and one guard lock). The average elevation difference between the locks is 14.2 meters. It is possible to design a turbine with ~95% efficiency for a well-defined pressure drop anywhere between 14-100 meters; either Kaplan or Francis turbines can meet these targets if the flow is well-controlled. It does appear that a kind of modified Francis turbine with adjustable blades (the Deriaz turbine) may have advantages in terms of pumping efficiency. (In general the viscous losses are higher when a turbine is reversed and runs in pumping mode, so improving efficiency in pumping mode is a big deal. Reversible turbines with fixed blades cannot be optimized for both pumping and turbine mode; the Deriaz gets closer to optimum efficiency in both pumping mode and turbine mode.)

If we take the total head loss due to viscous dissipation in the canals per se to be 2.0 meters, the remaining head pressure through each of the seven identical turbines would be 13.9 meters of head. It is quite feasible to specify and buy turbines that have very high efficiency (>93%) between 13.9 and 14.2 meters of head. The point of this is that there exists an optimum number of equal-pressure steps to achieve the best balance of cost efficiency of the locks for moving shipping and for generation of electricity in a dual purpose upgraded Welland Canal. This is one option we will consider.

A 10 GW (output) pumped storage facility would imply back-and-forth water flows between the lakes of approximately 418,000 cubic feet per second (11,800 cubic meters/second), when maximum power is being generated, or when maximum reverse pumping is occurring. This is about twice the average flow of the Niagara River. This 10 GW facility could operate 130 hours in one mode without exceeding the proposed maximum 30-cm effect on Lake Ontario level. In a more realistic daily cycle mode, in which pumping and hydropower generation each occurs 10 hours per day, the daily shift in the level of Lake Ontario due to pumped storage would be 2.2 cm. (Lake Ontario is smaller than Lake Erie, so it experiences a larger level change.)

The proposed pumped storage capability combined with a reinforced regional HVDC power grid would decrease the total electric generating capacity and spinning reserves that would be needed to satisfy the region's electricity appetite, because hydroelectric power is relatively easy to bring online in response to demand fluctuations. It takes even less time to bring hydroelectric power generating capacity online than gas turbines. This project would decrease both the capital and fuel costs for peak power, while also improving system reliability. The proposed facility would be unique among pumped storage facilities in that the ratio of energy storage capacity to power output capacity (the potential hours of continuous operation in one mode, energy storage or energy retrieval, prior to exhausting the reservoir capacity) would be exceptionally large, at least for facilities that would be likely to be built initially. For example, even if an exceptionally large 54 GW of pumped storage capacity were installed (77.4 GW input in storage mode, 54.2 GW output in generation mode), the facility would be capable of operating for a full 24 hours in one mode. It is far more likely that a facility with an output of around 10 GW would be built, which implies the potential to operate 5.4 days at full output (not a realistic scenario, since even in periods of very high daytime demand, the nighttime demand would drop off enough to allow at least some recharging of the upper reservoir by pumping). This high storage capacity would give very important advantages for managing extended peak load periods, which typically occur on the hottest and coldest days of the year, and which could extend for periods of weeks in the worst case. This large energy

storage capacity would also mitigate the effects of unplanned outages of large generators, and weeklong periods of low wind in the case of a system heavily dependent on wind power.

The two main reasons to use pumped storage are load leveling and economic dispatch. The largest pumped storage facility that is operational in New York today is the Blenheim-Gilboa facility, which is strictly used for economic dispatch (storing inexpensive power at night, and generating it during peak periods during the day). There has been some discussion of using this facility for load leveling as well, but neither the present equipment nor the 2010 update of the equipment for this facility will give the degree of flexibility in output that is optimal for load leveling. In particular, all four turbines at Blenheim-Gilboa are the same size (290 megawatts each), so it is not possible to deliver the infinitely variable power output that is ideal for load leveling.

The particular design of the proposed new facility that would produce the least possible environmental impact would be based on tunnels to transport the water from Lake Erie to Lake Ontario (the turbine/pumping power stations could be anywhere along the tunnel in principle). We ran calculations on this option, and found that the required tunnel diameter for even a one GW facility with acceptable head loss would be considerably larger than the Niagara Tunnel Project, which is now under construction, and is being bored to a 14.4 meter diameter<sup>8</sup>). Even this massive tunnel, which will be 10.4 kilometers long when completed, will only support 0.15 GW of generation capacity. This implies that multiple tunnels would be required between Lake Erie and Lake Ontario to give acceptable energy loss at even one GW output capacity. We believe that a pair of surface canals would be much more economical, combined with relatively short tunnels to feed the penstocks for the pump/turbines which would be situated between the high canal at Lake Erie's level, and the low canal at Lake Ontario's level. The following section lays out the main argument against a tunnel-based approach. In what follows, reference is made to information available from any standard fluid mechanics text<sup>9</sup>.

1. Flow of an incompressible fluid through a closed conduit is described by the energy equation

$$[ p_1/\rho + v_1^2/2 + gz_1 ] - [ p_2/\rho + v_2^2/2 + gz_2 ] = h_l \quad (1)$$

where  $p$  = pressure,  $\rho$  = mass density,  $v$  = flow velocity,  $g$  = acceleration of gravity,  $z$  = static head height, and the subscripts define the upstream and downstream boundaries of the flow. The terms represent respectively pressure, kinetic and gravitational potential energy.

The difference between the total energy (summation of the three terms) at stations 1 and 2 appears on the right-hand side as the loss due to viscosity, conventionally termed 'head loss'  $h_l$  (for the present purpose, the so-called 'minor head losses' due to valves, fittings, etc. are neglected).

2. Head loss is expressed like kinetic energy, as a function of the velocity squared, multiplied by the ratio of conduit length to diameter  $L/D$  and a friction factor  $f$ , a characteristic of the conduit surface:

$$h_l = f (L/D) (v^2/2) \quad (2)$$

3. Regardless of conduit losses and neglecting turbine efficiency, the power that must be delivered to the turbine is equal to the kinetic energy  $E_k$  of the flow per unit time:

$$E_k = mv^2/2$$

where  $m$  = mass and  $v$  = velocity. Dividing this by unit time  $t$  gives power  $P$ ,

$$P = mv^2/2t$$

The mass is the product of density  $\rho$  and volume  $V$ , hence

$$P = \rho Vv^2/2t$$

For a cylindrical conduit, the volume swept out by the flow per unit time is  $V = \pi D^2/4L$ . Substituting,

$$P = \pi \rho D^2 Lv^2/8t$$

But  $L/t$ , the movement of the flow per unit time, is simply the velocity. Hence

$$P = \pi \rho D^2 v^3/8$$

which agrees with the generality in hydrodynamics that power is proportional to the cube of velocity. Rearranging, the velocity is

$$v = [8P/\pi\rho D^2]^{1/3} \quad (3)$$

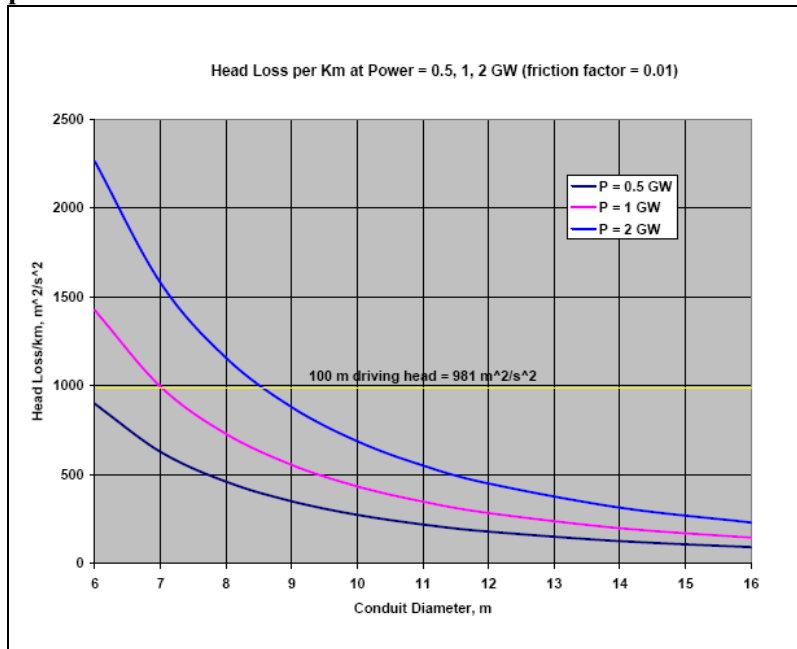
Thus for constant power delivered, velocity in the conduit varies as  $D^{-2/3}$ .

4. These equations can be used to construct a plot showing head loss versus conduit diameter for given power. Velocity from (3) is substituted in (2) with an assumed friction factor  $f$  of 0.01, typical of a concrete surface. Because the head loss is linear in the parameter  $L/D$ , the plot can be put on a per-kilometer basis to illustrate how limited the conduit length must be with respect to the driving head.

Figure 2 is a plot of head loss for power levels of 0.5, 1, and 2 GW (1 GW = 1E9 N-m/s) versus conduit diameter assuming  $f = 0.01$ , a midrange value for a very large concrete conduit. The yellow horizontal line

superimposed is the available driving head  $gh$  of  $981 \text{ m}^2/\text{s}^2$  for the assumed 100m height difference, for comparison. Clearly, head loss over the approximately 35 km path length would be too high for even a one GW pumped storage system to work efficiently.

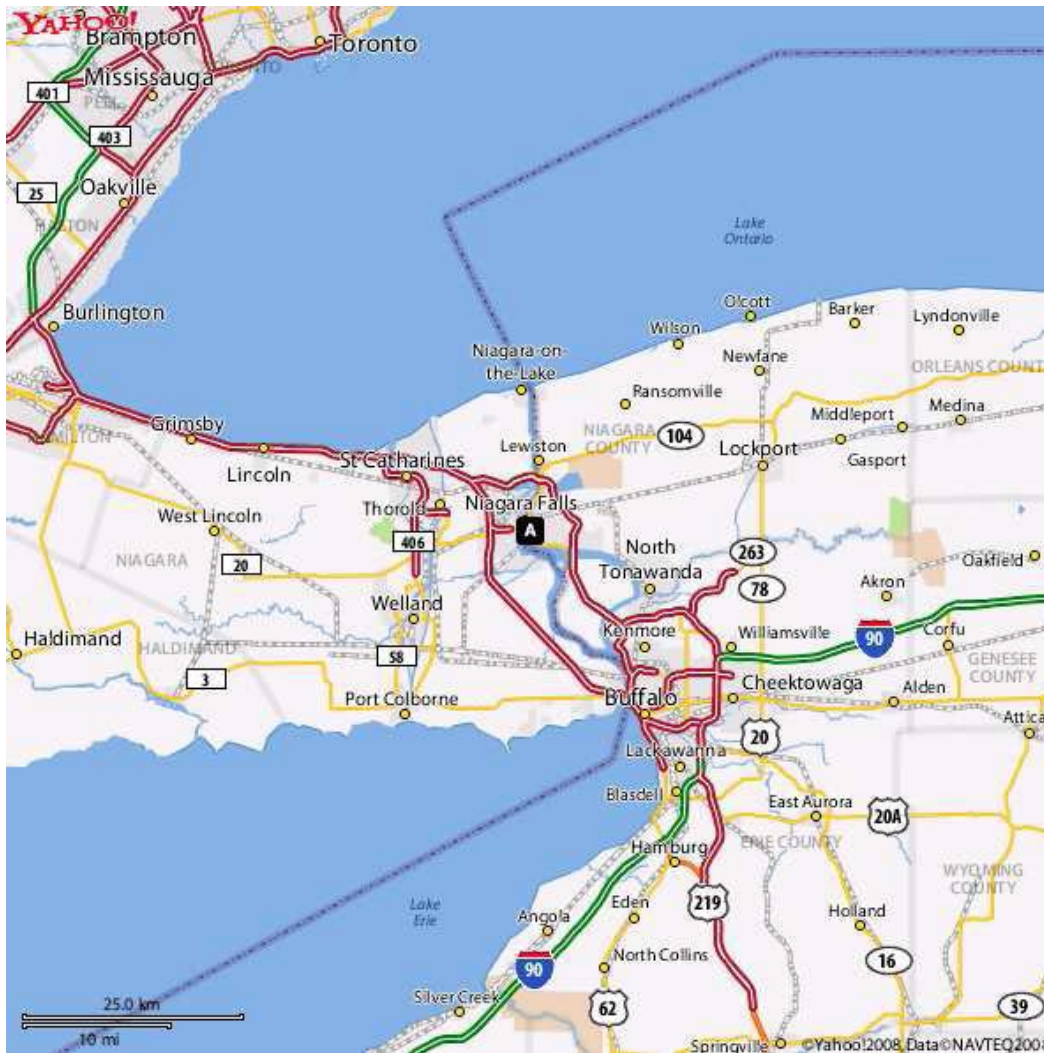
**Figure 2: Head Loss per Kilometer as a Function of Conduit Diameter**



It is apparent that a conduit of any reasonable diameter cannot deliver gigawatt-range hydraulic power over the relevant distance (~35 km), as the velocities required lead to unacceptably high losses. The additional input power required for pumping back upstream will be comparable.

This simplistic analysis does not even begin to consider the problem of transients if the system is used for demand power: reversing under the huge inertia of the long water column, maintenance of sufficient net positive suction head to the pump to prevent cavitation, and so on.

In summary, a closed conduit is not practical for the Lakes Erie/Ontario water-raising energy storage scheme. It appears that a deep canal linked to Lake Erie would have to be brought to within close proximity to a similar deep canal linked to Lake Ontario to implement pumped storage between the lakes. Alternatively, multiple steps of canal level could occur between Lake Erie and Lake Ontario, with low-head turbines between the canal segments. The topography suggests that the best, most direct route for these surface canals or tunnels would be through Canada, slightly to the west of Port Colborne, Ontario in the south and Saint Catherines in the north; it is about 35 km from Lake Erie to Lake Ontario in this region (see the low resolution map below, Figure 3). There is already a major shipping canal linking Lake Erie to Lake Ontario slightly to the east of this (the Welland Canal). We propose to look at potential routes for the power canals to the west of the Welland Canal. We have lined up a well qualified geologist from nearby Brock University in Ontario to give realistic feedback on the rock formations in that area; we will consider geology, topography, and settlement patterns in suggesting a best route. We will also seek input from local governments in the area.

**Figure 3: Map of the Isthmus Area**

The power canals are likely to be the biggest part of the cost of the project. At 10 GW output capacity, and if the canals are 20 meters deep, they would need to be 590 meters wide to maintain an average water velocity of one meter/second (a typical target in many power canals). Deeper canals, with depth nearly equal to width would be most desirable from the viewpoint of head loss, but would probably be more expensive to construct. One possibility is that the excavated rock might have value as concrete aggregate; selling the mined rock, even at a low price, could help the economics of construction of surface canals. We will game out various canal shape factors; It may be possible to meet the 2.5% head loss target with water velocity as high as 5 m/s. In this scenario, acceleration of the water to 5 m/s would consume 1.27 meters of head pressure, about half of the available head for moving the water to the turbines given the target of 2.5% maximum head loss for transporting water to the turbines. Achieving a high water velocity to minimize the width and depth of the canals is highly desirable, and this may not be compatible with the idea of a multiple step canal with small turbines between canal segments at different heights (although the turbine outputs could in principle inject water into the lower channel with the same forward velocity that the water had in the upper canal, preserving the forward momentum of the water).

**A WIND ENERGY PROPOSAL FOR ONTARIO**

The proposal outlined here deals with the development of wind energy with a new twist: Great Lakes energy storage. But first, let us look at some figures.

The Electricity Conservation and Supply Task Force commissioned by the McGuinty government reported in January '04 that even if we adopt "aggressive" conservation measures the withdrawing of coal fired generation by 2007 and the retiring of nuclear generating plants as they come to the end of their lives (a total of 80% of generating capacity) Ontario will have a shortfall of about 25,000 megawatt (MW) by the year 2020. Energy Minister Dwight Duncan in speaking to the Empire Club of Toronto April 15, '04 estimated that replacing this generating capacity would cost between 25 and 40 billion dollars.

On November 24, '04 the Ontario government announced it was purchasing green power, (mostly wind turbines) for \$1.77 million/megawatt. Ontario has finally begun the process of buying wind energy, the greenest and ultimately the cheapest form of energy and at 32% per year the fastest growing energy source.

Due to subsidies to the nuclear oil and gas industry and to the former Ontario Hydro monopoly which left taxpayers with a debt of \$20 billion dollars the price of electricity has historically been unrealistically low. The result is that per capita electric power consumption in Ontario is double that of countries like Germany. We have become wasteful in our use of electricity in our homes and in our industries. We are now paying the price with obsolete electrical equipment, air pollution, high rates of asthma and the prospect of heavy penalties if we do not meet our commitment under the Kyoto agreement.

We need to change our wasteful equipment and habits and we also need to build cleaner electricity generating equipment.

**The Wind Energy Possibility**

This proposal looks in a preliminary manner at the possibility of supplying almost the entire anticipated shortfall of generating capacity with wind turbines. Wind as an energy source is clean, renewable and free. But constant the wind is not. Where wind energy is well established as in northern Europe, other forms of energy such as from fossil fuels are required to take up the slack caused when the wind is not strong. In North America at this time wind energy supplies such a small proportion of the total electrical output that it can enter the grid with little effect. If, however, we are to build a system that relies mainly on wind energy, we need to have a back up for when there is no wind. Contrary to conventional thinking we do not need to build nuclear and/or fossil fuel fired generators as backup. This is where our unique geography can make the difference.

Lake Ontario, the lowest of the five Great Lakes, is 99 meters below Lake Erie. Water falling into Lake Ontario at Niagara has given us cheap and clean electricity for almost a century. The potential of the relationship of these lakes has, however, not been fully realized. Not only can we benefit from water that flows naturally, we can pump water back up from Lake Ontario to Lake Erie when we have a surplus of power at night and weekends and draw it down when electrical loads peak such as in the coldest part of winter or in a heat wave in summer. There is already some pumping up of water from Lake Ontario into a 3 square kilometer pond above the Adam Beck generating station on the Lower Niagara River and the technology is familiar. Lake Erie with an area of 25,720 square kilometers is 8,470 times larger in area than the pond. Lake Ontario is only slightly smaller. The pond in relation to Lake Erie is as a drop in a bucket.

The ability to raise a large volume of water a substantial height from one enormous lake to another enormous lake with little effect on the water level in either gives us a scale of energy storage potential found nowhere else in the world.

### **The Cost of the Wind Turbine Component**

Generating capacity must exceed peak loads to avoid importing energy at high cost. In estimating the number of wind turbines needed we can count on hydro electric power using water previously pumped up into Lake Erie to take care of the peak load requirement. We shall then arrive at the wind power requirement and its cost by meeting the energy requirement rather than the peak load requirement. The peak load requirement and cost will be largely met by the “backup” facility shown later.

In 2002 Ontario Power Generation (OPG) generated 115.8 terawatt-hours of electricity or 317 gigawatt-hrs per day on average. (With a capacity of 22,733 megawatts it could have produced  $24 \times 22,733 = 545$  gigawatt-hrs of energy/day. The average utilization factor was therefore  $317/545 = 58\%$ .)

Ontario also imported 7% of its electrical energy for a total consumption of 123.9 terawatt-hours. Of Ontario’s production, 71% or 88 terawatt-hours came from nuclear and fossil fuels. Water power supplied about 27 terawatt-hours.

Ontario’s population is expected to increase to about 15 million by 2020, an increase of 25%. If the per capita rate of energy consumption per capita remained constant, by 2020 we would consume 154.9 terawatt-hours/year. With realistic pricing, smart metering, better technology and incentives we can reduce that by half to about 77.4 terawatt-hours/year. A number of authorities on energy can show that this is possible.

If the existing hydroelectric production of 27 terawatt-hours/year is increased to 30 terawatt hours/year together with other green energy, the wind power objective will then be  $77.4 - 30 = 47.7$  terawatt-hours/year.

A 1 megawatt wind turbine running at full capacity 24 hours a day for 365 days could deliver 8760 megawatt-hours/year, but because the wind is often calm, each such turbine will on average deliver less than this, about 2,600 megawatt-hours/year or 0.0026 terawatt-hour/year. The requirement is then  $47.7/0.0026 = 18,300$  wind turbines approximately. In recent contracts for wind energy the cost per megawatt has been about \$1.77 million. Total cost of wind turbines would therefore be about  $\$1.77 \text{ million} \times 18,300 = \$32.5 \text{ billion}$ . This volume of purchases will probably result in lower costs.

### **The Cost of the Stored Hydro Power Component, the “Backup”**

Whenever there is more electricity generated by the wind than there is demand, water will be pumped from Lake Ontario to Lake Erie. Allowing a 28% loss for pumping up from Lake Ontario results in a Lake Erie water storage utilization factor of 0.72. Losses due to evaporation will be small since the water pumped up will soon be drawn down again.

To estimate the cost of the additional hydro electric generator/pumps required assume that on a hot but calm day in summer (probably the worst case) the output from the wind turbines drops to 20% of rated 18,300 megawatt capacity. The remaining 80%, or 14,600 megawatt, must come from the new hydroelectric generators. The estimated cost in June of 2004 of the proposed Beck 3 generators, was \$1.633 million/megawatt including a new tunnel to bring water from Lake Erie. The cost of providing 14,600 megawatts of new hydroelectric generating capacity taking into account the 0.655 utilization factor stated earlier would be  $14,600 \times \$1.633 \times 1/.72 \text{ million} = \$33.1 \text{ billion}$ .

### **Total Cost**

The estimated cost over 15 years to meet the projected shortfall of electrical generation in Ontario would be  $\$32.5 \text{ billion for the wind turbines} + \$33.1 \text{ billion for the hydroelectric generators} = \$65.6 \text{ billion}$ .

Although this is an enormous cost and is about twice the recent projected cost of nuclear power generation over the same time period, the past record of nuclear generating costs suggests that recent estimates may not be realistic. The lifetime of nuclear facilities has been disappointing whereas that of wind turbines has not.

### **The Effect on the Lakes**

The following calculations will quantify the potential storage in Lake Erie and show how small a variation of lake levels is needed to supply the required back up energy.

When 1 cubic meter of water, weighing 1000 kilograms falls through a distance of 98 meters, the gravitational energy change is 960400 joules. If this takes place over a time of 1 hour, the power is 960400 joules / 3600 seconds or 267 watts. If the efficiency of conversion of gravitational energy into electrical energy is 95%, the electrical power derived from 1 cubic meter of water is  $0.95 \times 267 = 254$  watts or 0.000254 megawatts.

Therefore to generate 14,600 megawatts will require  $14,600/0.000254 = 58$  million cubic meters per hour. In one day  $58 \times 24 = 1392$  million cubic meters of water would be drawn down.

The area of Lake Erie is 25,720 square kilometers. The volume of 1 cm. of height at the surface of lake Erie is 257 million cubic meters. When 1392 million cubic meters of water is withdrawn the lake will drop  $1392/257 = 5.4$  cm. Should a similar storage strategy occur on the U.S. side of the lake, the variation in lake level on account of both countries would be 10.8 cm. an amount that would seem acceptable.

Nobody wants to see the level of Lake Erie lowered in order to produce electricity. This proposal requires no permanent lowering of the lake level. The water transfer should be thought of like a charge account, not a credit account. The draw down from Lake Erie should never be more than the amount previously put into it using surplus wind power.

### **The NIMBY (not in my back yard) Problem**

If all turbines were of the 3 MW size, 6,115 of them would be required.

No one but the most ardent wind aficionado wants a windmill in his or her backyard. Situating them in Lake Erie and in shallow waters at the eastern end of Lake Ontario is one solution; objections to the sight and sound would be minimized. Virtually all new wind turbines to be built in Denmark, a leader in wind power, will be in coastal waters. The cost is a little higher but this is offset by the stronger winds over waters. Lake Erie is relatively shallow which makes the cost of installation reasonable. Another desirable location with steady winds is Wolfe Island at the eastern end of Lake Ontario and shoals to the west of the island.

Wind turbines need to be spaced far enough apart so that they do not interfere significantly with the wind each of them will receive. A wind farm requires about 0.065 square kilometres per MW of generating capacity. If we require 18,346 MW of capacity, the area of wind farms will need to be  $0.065 \times 18,300 = 1,190$  square kilometres. The area of the Canadian side of Lake Erie is 12,800 sq. kilometers. Even if all the wind turbines were placed in Lake Erie, the area affected would only be 9.3 % of the lake. In areas with a depth of up to 15 meters, a depth presently considered economical, there is about 580 square kilometres, enough for about 9,000 MW, nearly half the requirement. Research into siting in deeper waters is underway in other countries so that locating the majority of wind turbines in Lake Erie is a distinct possibility.

### **Advantages of Massive Wind Power with Great Lakes Storage**

- Zero fuel cost

- Operating cost predictability
- Investor security
- Short delivery time
- No green house gas emissions
- Large contribution to Kyoto obligation
- No nuclear spent fuel disposal costs or dangers
- Recycling value at end of life instead of enormous cost of burial of entire facility in the case of nuclear power
- No target for terrorists
- Minimal added distribution costs
- Close to usage, minimal distribution losses compared to imported hydro power from Manitoba or Labrador
- Large new industry with long term demand for product
- Long term R & D potential
- Large export potential
- Steady income to farmers for land based turbines
- Unaffected by drought

**Disclaimer:**

The intention of this proposal is to stimulate discussion about our energy needs.

Most of the above calculations are based on information taken from the web. As I am no authority on wind power, electrical energy, or finance, I hope that people with expertise in these areas and with more accurate information will examine this proposal and advise me of any serious errors, or perhaps come forward with better proposals.

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**Footnotes:**

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<sup>1</sup> Valentine, Harry: Electricity Today, April 2008 (page 63).

<sup>2</sup> *Hydroelectric Pumped Storage Technology: International Experience* by American Society of Civil Engineers Task Committee on Pumped Storage, Task Committee on Pumped Storage, American Society of Civil Engineers Published by ASCE Publications, 1996

<sup>3</sup> [http://www.robbinstbm.com/solutions/case\\_studies/niagara.shtml](http://www.robbinstbm.com/solutions/case_studies/niagara.shtml)

<sup>4</sup> *Hydroelectric Pumped Storage Technology: International Experience* by American Society of Civil Engineers Task Committee on Pumped Storage, Task Committee on Pumped Storage, American Society of Civil Engineers; Published by ASCE Publications, 1996

<sup>5</sup> Pumped Storage: Conference : Papers and discussions, edited by By T. H. Douglas, Published by Thomas Telford, 1990; ISBN 0727715860, 9780727715869, 449 pages

<sup>6</sup> Valentine, Harry: Electricity Today, April 2008 (page 63).

<sup>7</sup> "Hydraulic Turbine Efficiency, Canadian Journal of Civil Engineering; April 2001, Vol. 28 Issue 2, p238-253

<sup>8</sup> [http://www.robbinstbm.com/solutions/case\\_studies/niagara.shtml](http://www.robbinstbm.com/solutions/case_studies/niagara.shtml) ;

[http://www.opg.com/power/hydro/new\\_projects/ntp/index.asp](http://www.opg.com/power/hydro/new_projects/ntp/index.asp)

<sup>9</sup> For example: Shames, *Mechanics of Fluids*, McGraw-Hill 1962, or Fox and McDonald, *Introduction to Fluid Mechanics*, 3 ed., Wiley 1985