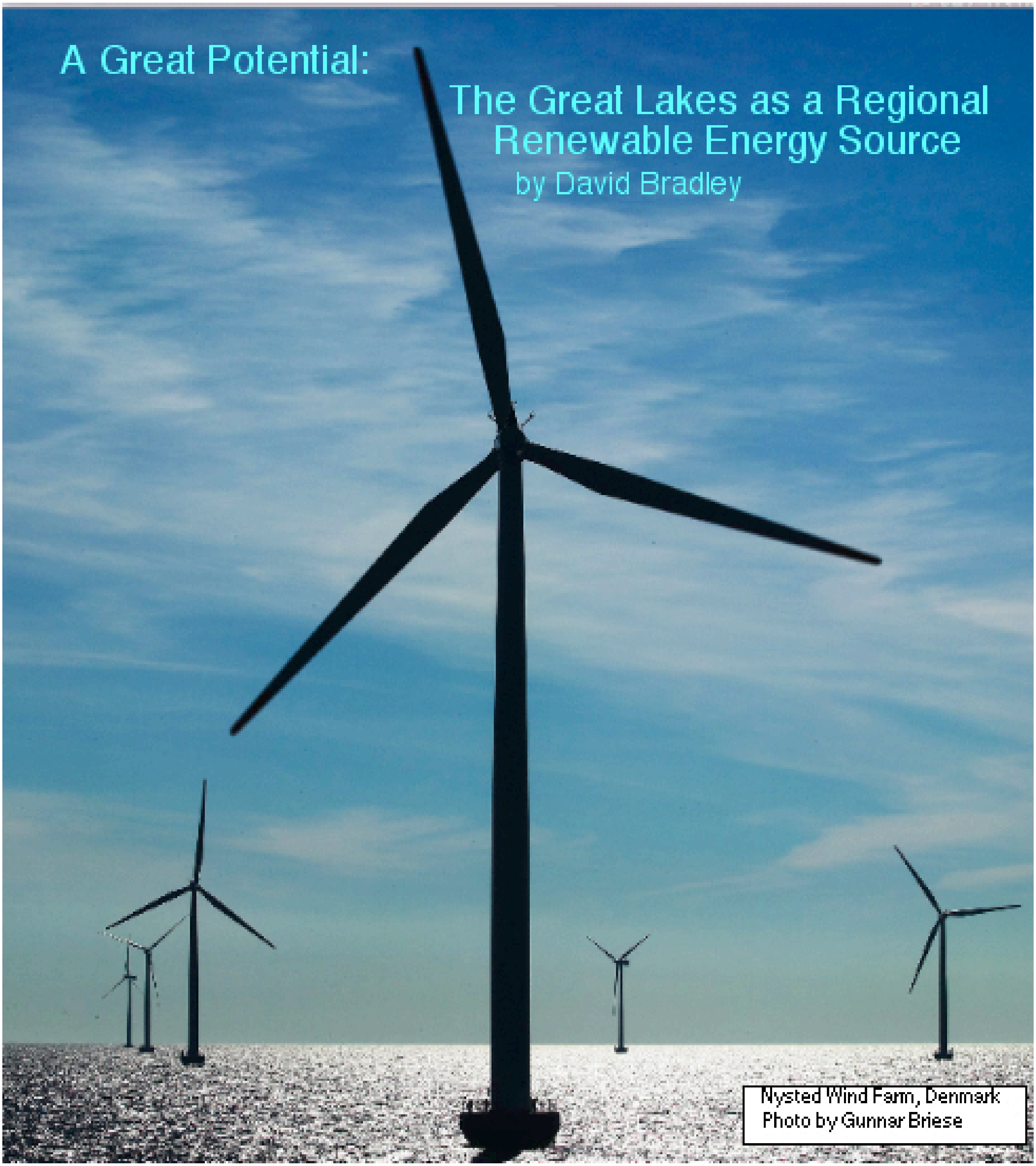
A Great Potential:

The Great Lakes as a Regional Renewable Energy Source

by David Bradley



Nysted Wind Farm, Denmark
Photo by Gunnar Briese

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ABSTRACT

Recent advances in wind turbine technology have made offshore wind turbines a practical means of bulk electrical production. Given the huge, usable (shallow) areas and significant wind resources of the Great Lakes, the region's entire electrical demand could be readily supplied by offshore wind turbines, at prices similar to and more stable than existing electrical rates. The combination of an existing high capacity grid, a significant supply of land and offshore wind resources and electrical demand in close proximity could be very beneficial, in many aspects.

In this paper, the offshore wind resource, estimated as 2.9 MW delivered power per km^2 of lake surface, is detailed. Some additional uses for this vast electrical energy source are discussed, especially with regards to hydrogen based fuels. The costs where hydrogen made from wind becomes equivalent to natural gas derived hydrogen are detailed. Approaches that can utilize electricity for transportation fuels are described, centered around hydrogen, ammonia, ethanol and carbon dioxide. Thus, wind power can be employed to improve the Great Lakes ecology, economy, and water quality, while at the same time providing for the entire electrical energy and some of the fuels for used for transportation in the region.

INTRODUCTION

Wind turbines are a non-polluting method of generating electricity. Large scale modern wind turbines are presently able to produce electricity in the United States at economically competitive rates in a significant portion of the country, depending upon the average wind speed of the location of the turbine. The production cost at a given location depends predominantly upon the wind speed, and to a lesser extent the type, size and configuration of the turbines. At an average wind speed of 7 meters/second (m/s), as measured at the center of the turbine hub, production costs are near 3 to 4 cents/kw-hr.

There are only a few renewable electrical energy sources that are less expensive than wind turbines, and these are very location specific – hydroelectric dams and high temperature geothermal sources. Wind turbines could easily supply over 4 times the current electrical energy demand in the U.S, which averages 440 gigawatts (GW). However, the geographic match of wind resources to electrical demand centers (which are the large metropolitan areas) is often non-existent, making this difficult to accomplish, but one of the regions where this does exist is in the Great Lakes region of the U.S. and Canada.

The placement of wind turbines in offshore locations is a relatively recent occurrence, and it is an offshoot of commercial wind turbine development. The necessary conditions where offshore wind farms make sense are the combination of a strong wind resource, large areas of shallow waters located near land in an area where a demand for the electricity exists. Since installation in water is more expensive than land installation, the wind resource must be sufficient to cover the added cost. Another way around this problem is to produce very large turbines, since the foundations tend to be a smaller fraction of the entire project, and fewer turbines are required for a given electrical production rate. In any case, the manufactured electricity has to be sold to pay off the investment costs, and competing forms of electrical production put limits on the construction of any new generating facilities that are not cost effective. As of 2004, the unsubsidized production costs of 3 to 4 vents/kw-hr are less than the fuel cost of natural gas used in a combined cycle production plant that is not a co-generating facility. The Great Lakes happen to have large areas of potentially usable shallow waters that could be employed for offshore wind farms. These zones could generate vast quantities of electricity, which is far greater than the regional land based wind turbine potential of 110 gigawatts (GW).

All energy use is not in the form of electricity, or even electrically derived to any significant extent. There are two other major uses for energy – for heat and transportation. In addition, large amounts of hydrocarbons are employed as chemical feedstocks or as a source of hydrogen for ammonia production. At the present time, oil and natural gas are often referred to as “energy”, although this is not always the case.

The combined onshore and offshore wind derived electricity could also be employed to produce much of the transportation fuels used in the region once the electrical demand is satisfied. For example, non-renewable, crude oil derived fuels such as gasoline could be replaced with ethanol, or with “artificial” gasoline made from methanol and ethanol. These alcohols can made from renewable sources, including significant amounts of wind turbine derived electricity. Such fuels would be examples of renewable energy (from wind turbines) replacing crude oil derived gasoline and oil in transportation uses, and this would have several benefits to the Great Lakes region. This would extend the utility of wind turbines as a way to lessen the planetary anthropogenic carbon dioxide emission rate in a significant manner. This approach would also be very practical, and could be readily implemented in an incremental manner that does not necessarily require the development of a new technology for powering automobiles or for producing new varieties of electrical energy storage systems.

The potential wind turbine production capacity in the Great Lakes region is more than 249 GW offshore, and averages 3.0 MW of average delivered power per km^2 of lake surface. The onshore average capacity is near 110 GW (this includes the estimated wind resources of Minnesota, Michigan, New York, Pennsylvania, Ohio, Indiana, Illinois and Wisconsin) in the U.S; most of the land-based potential is located in Minnesota in areas that are the farthest distance from the lakes in that state. Ontario also has a huge land based potential, partly due to its massive size. The combined 359 GW is equal to approximately 80 % of the non-renewable electrical production in the U.S. and Canada, and much more than the regional consumption of 125 GW (Ontario included). Much of this electricity can be made at similar costs to the polluting technologies of nuclear fission, oil and gas consumption and even coal combustion.

This paper begins with a description of the electricity that could be produced with wind turbines located on the Great Lakes. Since the electrical production possibilities are so large, the potential exists to use the electricity for uses other than for powering devices such as lighting, electronics and motors. Next, some effective methods where this electricity could be employed in transportation applications are detailed. Basically, the approach is to try and substitute gasoline with ethanol or similar bio-fuels, as long as these are made with renewable energy and fuels. Since most fuel ethanol is made by fermentation of crops such as corn, attempts could be made to minimize the use of fossil fuels in their production, such as with the fertilizer used to grow them at economically viable rates. Another possibility would be the reduction of the carbon dioxide by-product from the fermentation into fuels with hydrogen. Both the commercial scale ammonia synthesis and carbon dioxide reductions require the use of mass quantities of hydrogen, which can be obtained by the electrolysis of water. While this is not quite economically competitive with the natural gas route of hydrogen synthesis, the cost equivalence point seems to be coming in the near future. This will inevitably occur, since natural gas costs are rising, while wind turbine electricity is becoming less expensive, but “inevitable” does not necessarily provide the known date when this will occur.

BACKGROUND

The Great Lakes have been utilized by humans ever since they were discovered over 10,000 years ago. Initially, the human impact was inconsequential, mostly for transportation, dinking and fishing, and was done by a relatively small number of people, so any adverse affect upon the ecology was minimal. This changed in a dramatic manner once European "civilization" and European-derived settlers arrived and began colonizing the region. Europeans also viewed the relationship between humans and their environment very differently from the North American Indians, especially in religious, philosophical and economic terms. For instance, the "Euoroview" prevailing interpretation of Christianity, in effect, was that nature existed for the benefit of mankind. This became beneficial for Christians, and especially certain Christians, above all others.

In a relatively short span of time, the Great Lakes region was conquered and inhabited by the large numbers of European descended settlers. The lakes facilitated industry and trade, and there were significant minerals (copper, iron, gold) and enormous amounts of very high quality timber that could be extracted and harvested. The Great Lakes proved to be the least expensive transportation route for bulk quantities of goods from the Midwest to the northeastern part of the U.S. and Canada, as well as Europe. By the early 20^{th} century, the invention of electricity and refinement of industrial practices in steel, manufacturing, chemicals and paper led to a huge expansion of many cities, industrial facilities and subsequent demands upon the lakes. The first noticeable pollution strains were made evident by outbreaks of sewage carried diseases, but eventually several other stresses were placed upon the Great Lakes ecosystem, such as eutrofication, chemical contamination and alien species invasion (for example, zebra muscles and lampreys).

At this early stage of the 21^{st} century, nearly 38 million people live in the Great Lakes watershed/St. Lawrence River, including the very large metropolitan areas of Chicago, Detroit, Cleveland, Toronto and Montreal. Despite the recent evisceration of a significant portion of the industrial base in the region, a significant shipping still exists on the Great Lakes, especially related to iron ore, coal, chemicals, oil, manufactured items and grain shipments. Most of the sewage and other point pollution sources have been at least partly remedied, and the lakes are generally free of the major problems of eutrofication and water borne diseases, although improvements upon the current situation are certainly possible. The lakes are still used as the major source of drinking water for many of the 38 million people living near them, and as a source of process and cooling water for a large number of industries. One industry that uses a very large amount of lake cooling is the electric power generation industry, with coal and nuclear fuels as their primary energy source. Around the shores of the Great Lakes, over 150 to 200 GW of "waste heat" is dumped into the lakes in the process of process of producing approximately 50 to 75 GW of electrical power.

The use and wisdom of using the lakes for human's purposes (for cooling, drinking, sewage disposal, industrial processes and shipping) is no longer even questioned. In general, the only constraints on this "right" of usage are degree to which the consequences are found (or held) to be adverse relative to the benefits obtained, which is open to an enormous range of interpretation. One particular use of note is the use of the lakes as a coolant sink for thermal electric power plants. Without this "source of cold", the plant operating efficiencies would be lower and their electrical production costs would be higher. In some cases, the consequences of thermal pollution have forced the use of the less efficient/more expensive evaporative cooling systems, which still require a source of a large amount of water. The fossil fueled thermal plants are a significant source of regional and global carbon dioxide emissions. The coal fired fossil fueled plants are also sources of acid rain, mercury and other pollutants of the lakes via deposition of these airborne pollutants. Nuclear plants also carry special pollution risks best epitomized by the Chernobyl disaster. To date, there have been two near misses in that category for Great lakes nuclear plants – the Fermi 1 (near Detroit) partial core meltdown and recent containment vessel wall corrosion at the Besse-Davis plant (located between Toledo and Cleveland).

POTENTIAL WIND TURBINE ENERGY PRODUCTION

A relatively new option in electrical production has been evolving over the last 25 years – wind turbines. A variant is the offshore wind turbine; the oldest commercial scale offshore wind turbine array has been operating for 13 years in Denmark. The newer wind turbines (2000 to 2003) are very large machines (see figure 1). Once installed, wind turbines produce electricity without undesirable by-products such as air pollution, greenhouse gas emissions, significant thermal pollution, unwanted nuclear waste by-products or possible nuclear contamination. Given the recent pricing trends for oil and natural gas, offshore wind turbines on the Great Lakes have a significant potential as an electrical generation technique strictly on economic terms. They could also have a significant ecological, environmental, economic and social impact in this region. In addition, installed wind turbines generally have an energy payback time of one to three months, which means that any energy made after this point has a zero net contribution to Global Warming.

In 2003, 282 megawatts of offshore wind turbine capacity was installed in Europe – 122 machines at an average of 2.3 MW per machine. These units were installed in the Irish Sea, North Sea and Baltic Sea, which are regions with similar or even more extreme climates than exist in the Great Lakes. The average production cost for these units varies with the wind speeds and monetary costs (interest rates on the capital used to manufacture and install them), but should average between 3 to 5 cents per kw-hr. Cost information can also be deduced from the existing offshore windfarms. By 2010, over 15,000 MW of offshore wind farm capacity is planned for northern Europe, with Germany and Great Britain expected to have the largest installed offshore capacity. These units will be fully integrated into the various European electrical grids, with pumped hydroelectric energy storage facilities as backup power units.

Cable pulling. The cable is pulled through the J-tube - here, a turbine with three cable connections.

Views of the Homs Rev Wind Turbines:

Vestas V80 wind turbines
blade length = 39 meters, spacing = 500 meters
hub height is 70 meters above the water surface

Figure 1
Offshore Wind Turbine Views

Installing wind turbines on the Great Lakes would be another case of humans using the lakes for their own benefit. However, the major objections to such developments are likely to be the effect of the turbines on the views that humans have of the lakes, and not any significant adverse ecological effects (if any exists) that the turbines might instigate.

Wind turbine foundations in the lakes would probably be very beneficial for fish growth, and the replacement of coal, oil, gas and nuclear powered electrical generating units that are situated along the shoreline would result in less overall damaging pollution to the lakes and their watersheds. The effect on bird migration/ birdlife would be minimal. The most troublesome problem may be disturbances of the lakebed sediments that result in the recycle of toxic contaminants (such as polyhalogenated biphenyls) trapped in these sediments back into the water column during the installation of offshore turbines.

MODERN COMMERICAL SCALE WIND TURBINES

Modern, commercial scale wind turbines all share similar characteristics, as these have been "market tested" and found to be economically and operationally superior to other designs. A cut-away diagram of one is shown in Figure 2.

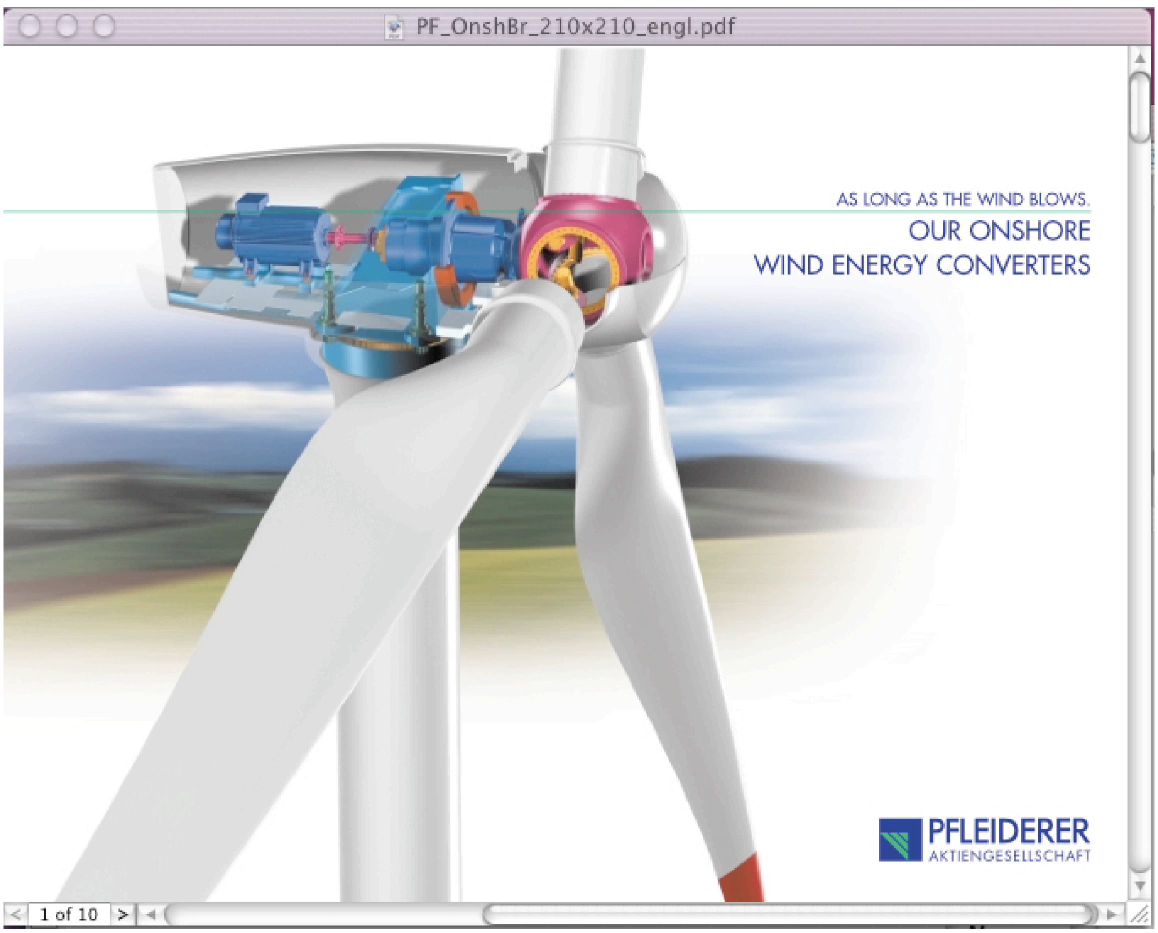

Figure 2
From Pfleiderer Product Brochure PF_OnshBr_210x210_engl.pdf, page1

These turbines are horizontal axis units (the rotor axis is parallel to the wind direction, and rotor plane is perpendicular to the wind direction), and consist of a foundation, support tower, nacelle and 3 rotor blades. The foundation is needed to support the tower and nacelle/blade assembly as well as to prevent it from being pushed over as a result of the wind. The tower supports the nacelle/blade apparatus, and also projects the blades into faster wind speeds that are present far above the surface. Inside the nacelle are housed the bearings for the rotor shaft, any gearing needed to increase the rotor speed, the generator and a series of controls and ancillary systems (hydraulics, lubrication, generator cooling, rotor brakes and nacelle orientation). The blades are usually constructed of fiber reinforced polymer resin composites (usually fiberglass, but sometimes wood and carbon fiber, too), and are hollow for the most part. The pitch of the blade can be adjusted to suit wind conditions as well as to create an aerodynamic stall condition, as required. The blades must be somewhat flexible, designed to be fatigue resistant and to have the largest strength to weight ratio as is possible, within the necessary production cost parameters.

Most wind turbine towers are tapered hollow steel towers, which can be assembled in sections to heights of up to 100 meters or more. The foundations have to be designed to suit local soil conditions, and are usually made of reinforced concrete. Some offshore turbine foundations are made using the mono-pile design, which is a large “pipe” that is rammed into the ground to a sufficient depth, and then filled with reinforced concrete and/or crushed stone; the conventional tower is then attached to the top of the mono-pile. Other foundations are made of cast reinforced concrete (gravity foundations) onto which the tapered steel tower is placed. A modern multi-megawatt turbine tower is approximately 60 to 100 meters tall, between 3 to 4 meters in diameter at the base, and weighs between 150 to 250 tons. In Europe, reinforced concrete towers have recently been introduced, as have hybrid towers with reinforced concrete lower sections and steel upper sections. Such towers are less flexible than all steel towers with the same height, and this tower flexibility has become important as the size and height of the towers has increased beyond 80 meter heights. Some turbines feature a gearless design using special large diameter, multi-pole generators. Most turbines utilize a gear speed increaser and a smaller diameter 4 to 6 pole generator, which is very similar to a standard induction “squirrel cage” electric motor. The rotation rate of these turbines depends upon the rotor diameter and sometimes the wind speed (variable speed design), but it is usually between 6 to 30 rpm. Modern wind turbines feature remote control and monitoring capability, and now serve as electrical grid stabilizing points, due to the needed electronics required to keep the turbine electrical output in phase with the electrical grid operating frequency (either 50 or 60 Hz). The turbines have a cut-in speed, which is a minimum wind speed needed to produce rotation of the blades, and a cut-out speed, which is a maximum wind speed where the turbine rotation is stopped.

In 2003, wind turbine sales worldwide were more than $7.5 billion, and increasing at a 20 to 30 % yearly rate (the yearly growth rate varies, often in response to legislative actions). In 2003, the average new commercial scale wind turbine installed throughout the world was greater than 1 MW in capacity. Although smaller scale turbines can be ordered (100, 250, 400 kilowatts (kw)), most commercial scale wind turbines have a rated capacity of at least 600 kw. At present, over 90 % of the world's wind turbines are made in Europe, where over 75 % of the installed wind turbine capacity is located.

Wind power development is concentrated in Europe, but also is significant in North America, Japan, China, Australia, New Zealand as well as some parts of the Middle East and Northern Africa. Wind turbine installations can often be a function of certain government actions and legislation, especially in the United States, as well as other factors such as the world crude oil price and the available local fossil fuel resources. Total worldwide capacity as of January 2004 is near 40,000 MW (40 GW) of capacity, which translates into about 12 GW of continuous production. The efficiency of turbines (yearly output divided by maximum yearly capacity) continues to increase due to design improvements and higher turbine tower heights, which are often a requirement of the use of larger rotor diameters. These newer turbines are also extremely reliable, with repair and maintenance downtime averaging less than 2 % of a year (= 98 % "uptime"). To date, all offshore wind turbine installations are located in Europe.

The installation cost of a wind turbine can vary, depending upon the size of the wind farm, type and configuration of wind turbine and its location. On land, large wind turbines cost about $ 1.05 million per MW of capacity when installed in groups of about 10 or more. As the number of wind turbines per array increases, unit installation costs tend to decrease. Turbine tower heights can vary even for the same turbine, and are selected based upon the wind resource and economic issues; turbines with taller towers have higher installation costs but also greater energy production for a given wind resource. Finally, connection costs to the electrical grid can be up to $1 million per mile for high voltage transmission lines, and this is also a major consideration as to the wind turbine array location. Many sites are unable to have large turbines economically installed due to construction and transportation issues, or the lack of nearby electrical transmission lines.

MODERN OFFSHORE WIND TURBINES

The winds that flow across large bodies of waters such as oceans have certain beneficial characteristics compared to the winds that flow over land, as far as wind turbines are concerned. In general, the wind speeds over waters at a given height in the 5 to 150 meter range tend to be faster and less turbulent than the corresponding winds flowing over land, even flat, obstruction free areas, assuming that the same wind speeds are present at some defined height above the surface, such as 150 meters. Another advantage of offshore placement of wind turbines concerns the ease of transport, especially for the new, very large multi-megawatt size turbines. There is usually no competing surface use for the waters as there often is for land areas except as shipping lanes, especially those land areas near urban areas. Obviously, the construction of service roads is not relevant for water based wind turbines. The newer offshore wind turbines are very large, very sophisticated electrical production systems, where large size is important for the economic viability of these projects.

There are also some disadvantages that are associated with offshore turbines. The first one is the higher installation cost for offshore wind turbines (including the more expensive foundation, platform located substations and underwater power transmission lines). Capital requirements tend to be 25 to 40 % greater per MW of capacity for offshore wind turbines as compared to ones installed on land. The other added factor is the higher cost for servicing the wind turbines, or the need for very large, maritime cranes. There are also unique regulatory procedures that must be accommodated; in the U.S., all offshore turbine installations would need the approval of the Army Corps of Engineering, in addition to any state and local approvals. These approvals can be obtained when the prospective offshore developments are in compliance with the numerous laws and regulations pertaining to offshore developments, and a thorough environmental review has been conducted for the potential project.

The greater wind speeds present offshore result in greater energy production for a given wind turbine. The energy content of flowing air increases with the cube of the wind velocity and is linearly proportional to the air density. Air flowing over a cold lake will have a greater energy per unit volume of air relative to warmer air. The combination of increased air density relative to air flowing across land (and especially over elevated portions of land such as mountain ridges, where lower air pressure exists due to the higher altitude) and generally faster wind speeds at the turbine hub height makes are the major operational advantages for offshore locations. For example, if wind speeds at a given turbine hub height are 12 % faster offshore than on land at the same height, then approximately 1.4 times as much power can be produced offshore for a given turbine with an identical tower height. Another recent development is the production of the very large, multi-megawatt wind turbines. A brief list of some of the planned and currently operational "mega-turbines" is given in Table 1.

Table 1
Large Scale Wind Turbines for 2002-2005-Operational or Planned

Turbine Mfg / Model	Output MW	Tower Ht meters	Rotor / Blade meters		Date
Enercon E112	4.5	124	112	55	2002 op
Nordex N92	2.3	80 – 100	92	45	2002 op
GE 3.6s	3.6	75 – 100	104	50	2002 op
NEG-Micon NM90	2.75	80 – 100	90	44	2003 op
NEG-Micon NM110	4.2	80 – 120	110	54	2003 op
Vestas V90	3	80 - 100	90	44	2003 op
Nordex N115	5.0	100 – 115	115	56	2005 est
REPower MM125	5.0	80 – 125	125	61	2004 est
Oy	3.0	80 – 100	90	44	2004 est
Pfleiderer	5.0	90 – 120	120	58	2004 est

Currently, the largest two units operating in the world (developmental units made by Enercon, of Germany – see http://www.enercon.de) have capacity ratings of 4.5 MW, a 112 meter rotor diameter and a tower height of 124 meters. Each rotor blade is 55 meters (180 feet) long; transporting such devices over roads and even by trains is extremely difficult. The nacelles (power generating components) of these particular Enercon units each weigh a total of 440 tons. Items such as these can be easily transported by barge and ship, and have been designed with offshore installation in mind. The largest installed offshore turbine currently has a 3.6 MW capacity (made by General Electric). The greatest number of offshore turbines presently installed are either 2 MW or 2.3 MW in capacity; and most of these are presently installed offshore of Denmark in either the North or Baltic Sea. A list of installed offshore turbines is given in Table 2 (from http://www.offshorewindturbines.com).

Table 2
Installed Offshore Wind Turbines as of December, 2003

Location	Date	Unit MW	Capacity and Size* d x h	Number	Capacity MW
Vindeby, Dk	1991	0.45	40 x 40	11	5
Lely, Nl	1994	2.0		4	8
Tuno Knob, Dk	1995	0.6	45 x 40	10	6
Dronten, Nl	1996	0.6	44 x 40	19	11.4
Gotland, Se	1997	0.5	40 x 40	5	2.5
Blyth, GB	2000	2	66 x 60	2	4
Middelgrunden, Dk	2001	2	72 x 70	20	40
Uttgrunden, Se	2001	1.5	70 x 64	7	10.5
Tyye Stengrund, Se	2001	2	72 x 60	5	10
Horns Rev, Dk	2002	2	80 x 70	80	160
Samsoe,Dk	2003	2.3	82.5 x 70	10	23
Nysted , Dk	2003	2.3	82.5 x 70	72	165.6
Frederikshaven, Dk	2003	2.3, 3	to 92 x 80	4	10.6
North Hoyle, GB	2003	2 MW	80 x 60	30	60
Arklow Bank, Ire	2003	3.6 MW	104 x 75	7	25.2
Total to date				276	541.8

* Rotor diameter (d) by tower height (h) above water line, in meters

At present, the installation cost of offshore turbines is approximately 1.25 to 1.4 times that of onshore turbines, assuming that these turbines could even be installed in most inland locations. For the large units, land installation opportunities are limited to near shoreline locations, simply due to the difficulty of transporting many of the key components on land. Offshore units are generally expected to require less need for service, due to the lower wind turbulence that the rotor blades experience. The higher initial capital cost can be mitigated through the construction of very large wind turbine arrays. This has the effect of lowering the installation cost per unit, and is an approach that will soon be used in Great Britain and Germany, where arrays between 200 to 600 MW are planned for offshore wind turbine farms.

To date, offshore wind turbines have been installed at depths of up to 18 meters of water; 20 meter depths are usually considered the present state of the art, at least from a cost consideration. Many potential wind farms near Germany (with installation dates of 2005-2007) are planned for water depths of up to 40 meters. The very large turbines, on the order of 4 to 5 MW, are considered necessary to justify the added expense of these deeper water foundations.

THE GREAT LAKES WIND RESOURCES

The Great Lakes weather conditions have been monitored for several decades by the governments of Canada and the United States, largely to insure that shipping could be safely and effectively conducted as well as for general meteorological information. Thousands of shipwrecks have occurred in the last 200 years, often a result of stormy conditions on these lakes. One of the more infamous recent shipping accidents was in 1976, when the Edmund Fitzgerald, a 700 foot long iron ore freighter, snapped in half when it encountered a series of waves greater than 30 feet tall in Lake Superior in hurricane force winds. There are a series of weather monitoring buoys placed in the lakes, weather stations on islands and on the shores specifically designed for Great Lakes monitoring (see Figure 2). There are also numerous weather stations at locations near the coast, in towns, cities, and at airports, television and radio stations. In addition, a ship based weather condition reporting system is also employed during shipping season, which usually lasts from April to November. Thus, there are a considerable amount of data sources available with regard to wind speeds, for either the lake surface or at the coastline, as well as near the coast.

One of the more complete estimates of the Great Lake wind speeds was made for Canada in the 1970's, and is available through the Environment Canada website (see http://www.meds-sdmm.dfo-mpo.gc.ca/alphapro/wave/TDCAtlas/TDCAtlasGL.htm and http://www.meds-sdmm.dfo-mpo.gc.ca/alphapro/wave/TDCAtlas/TDCProducts.htm). The wind speeds for Lake Ontario, Erie and Michigan were assembled as an average, while Lake Huron was arranged in two sections and Lake Superior was arranged into three segments. Each lake or lake segment had over 45,000 readings of wind speeds either at or adjusted to a standard 10 meter height. The information in this Great Lakes Climate Atlas includes average wind speeds, wind speed distributions, as well as other information such as wave height and distributions. There exists one problem with the Lake Ontario data, which is corrected in Table 3.

Table 3
Average Wave Heights on the Great Lakes

Lake	Av Wind Speed * meters/second	Av Wave Height meters	Maximum Wave Height meters
Ontario	6.42	0.4	7.5
Erie	6.63	1.0	7.0
Huron, south	7.80	1.1	8.7
Huron, north	7.20	1.0	9.2
Huron, av	7.50	1.05	
Michigan	6.01	0.8	11.4
Superior, west	6.17	0.9	8.9
Superior, central	6.38	0.9	8.2
Superior, east	8.02	1.2	10.5
Superior, av	6.86	1.0	

* As measured in the last 20 years by buoys shoreline stations and other lake weather stations, referenced to 10 meters of height above the average water surface.

THE GREAT LAKES BATHYMETRY INFORMATION

Bathymetry refers to the mapping of water depth, and extensive information has been prepared with regard to water depth mapping of the Great Lakes. There is an obvious practical use for such information with regards to shipping; the accidental grounding of any vessel is unfortunate, and even more so when it is a 1000 foot long vessel. The bathymetry data has been used to arrange shipping routes and shipping channels, but it also has a tremendous utility with regards to the potential sites of offshore wind turbines.

The Great Lakes Bathymetry data have been available in a digitized format for over 30 years, and an even more accurate and updated version will soon be completed. It has been assembled on a per lake basis, so specific bathymetric data information can be readily recovered, once the unique format is addressed. This data can also be used to calculate the amount of lake areas with certain depths, as well as depth ranges. This data is shown in Table 4, and arranged in 0 to 20, 20 to 30 and 30 to 40 meter depths. The information is shown graphically in Figure 2, in particular for the 0 to 20 and 20 to 40 meter depth ranges. The raw bathymetric data for the Great Lakes have been compiled and digitized by the Great Lakes Environmental Research Laboratory (a unit of NOAA, the National Oceanic and Atmospheric Agency) and can be found online at:

http://www.glerl.noaa.gov/data/char/bathymetry.html

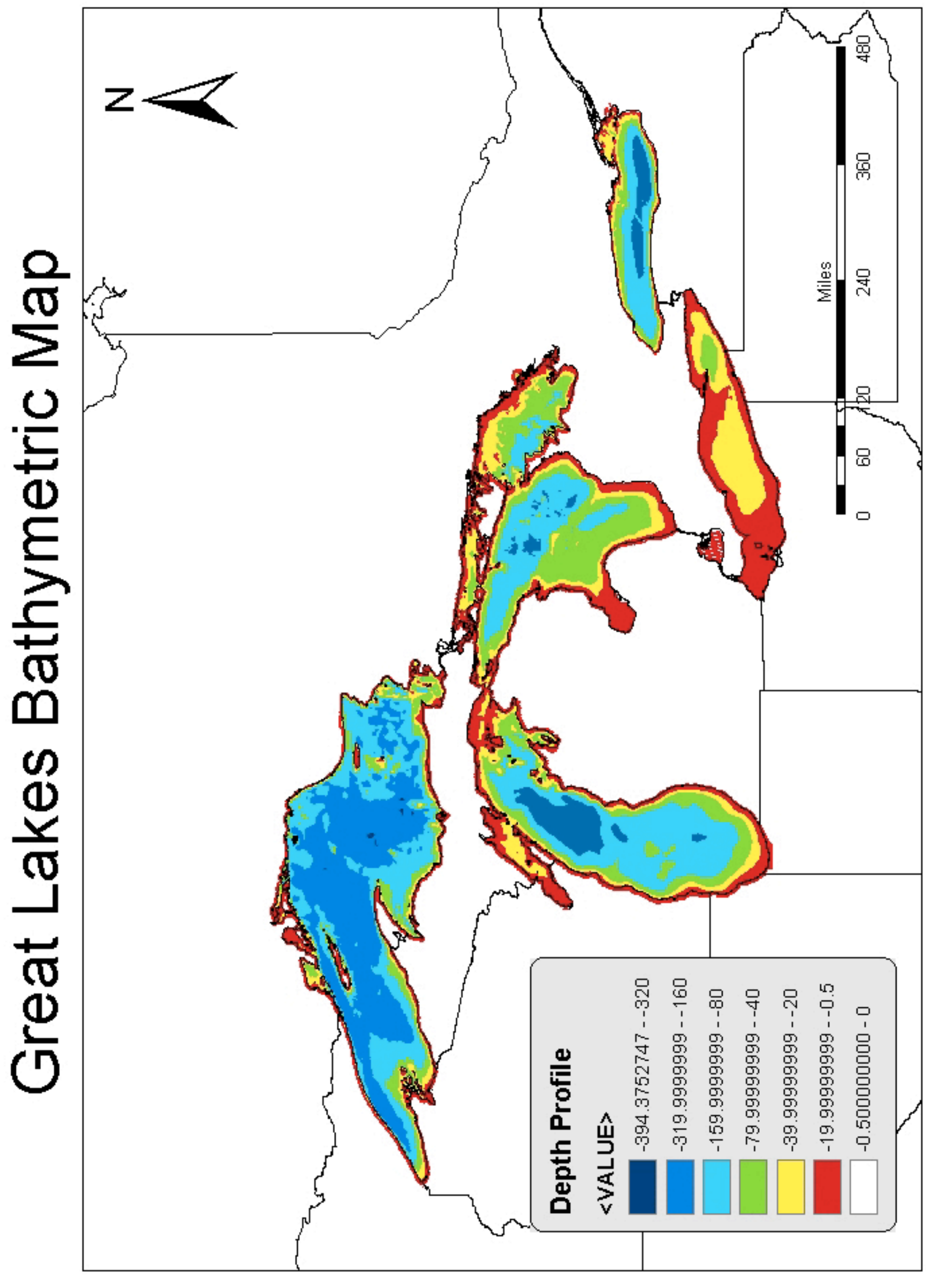

Figure 3
Great Lakes Bathymetry Map

Table 4
Great Lakes Bathymetry Summary

Lake	Total Surface Area (km^2)	Area (km^2) at Depth Ranges (meters) 0 to 20	20 to 30	30 to 40
Ontario	18,484	2,732	1,252	1,200
Erie	25,328	15,688	7,488	1,084
St. Clair	1,053	1,053	0	0
Huron	59,576	14,888	4,568	5,520
Michigan	59,196	12,176	4,612	3,094
Superior	82,396	6,092	2,180	2,712
Totals	246,033	52,629	20,100	13,610

Approximately 21.4 % of the Great Lakes have a depth between 0 to 20 meters, and could be currently considered as a feasible wind turbine location. The percentage of lake possible for wind turbine installation goes to 29.6 % and 35.1 % as the “workable depth” extends to 30 and ultimately to 40 meters. To put this in perspective, the maximum potential turbine area (86,339 km^2) would be a square with a length 183.6 miles. Obviously, not all sites could be used, but the potential area available for offshore wind turbine installation is very large. Similarly, the number of turbines that could be installed offshore is also very large. The lakes with the greatest potential usable area are Lake Erie, Huron and Michigan. The shallow areas in the northeastern part of Lake Huron are also associated with numerous islands; these islands also could be considered as potential wind turbine locations, with wind resources very similar to offshore winds, but with less expensive installation costs.

If 95 % of this these shallow areas are considered as potentially fit for wind turbine installations, the combined area would be 82,022 km^2. This is still a huge area, and constitutes about 33.2 % of the combined Great Lakes surface area. Most of the shallow areas of these lakes are fairly close to land, as there are very few “stranded” shallow areas in the central parts of the lakes that are surrounded by deeper waters. In general, the lake depths gradually increase with distance from the shoreline until a fairly constant depth is achieved (see Figure 3). Such an arrangement is extremely advantageous for offshore developments, since the lengths of high capacity underwater transmission lines, which are very expensive, can be minimized.

WIND POWER ESTIMATES

Modern wind turbines are devices that extract mechanical energy from the kinetic energy of the wind. The mechanical energy is seen as the rotation of a large turbine, which is almost always a set of three long, relatively slender blades set apart at 120 angles. The blades actually behave as airplane wings; air moving past the blades, which are tilted with respect to the oncoming air, creates a lower pressure region on the downwind side of the blades. The higher air pressure on the upwind side pushes on the blade area, which sets the blade in motion if the air is moving at some minimal velocity. The rotating blade is used to spin an electric generator, which then converts the rotational motion into electrical energy. While this appears to be simple, the actual science behind this process is quite complicated. Adding to this set of complications is the variable nature of the wind and the non-linear relationship of wind velocity to kinetic energy.

The wind speeds used to calculate the energy production are referenced to the turbine hub height, which is the center of the rotor. In general, wind speeds increase as the height above the surface increases, also in a non-linear fashion. Between the 2 to 300 meter heights is a region often referred to as the logarithmic wind speed region; the wind speed varies in a logarithmic manner with respect to the height above the surface. At the surface, the horizontal wind velocity is, in theory, zero, with respect to the surface. The logarithmic horizontal wind shear relationship also can be approximated by an exponential equation, which is much simpler to utilize. The wind shear exponent form can be just as valid as the more complicated form under certain circumstances.

The surface characteristics can have an important effect upon the wind speeds in the logarithmic layer. Surfaces that are smooth (such as ice covered lakes) do not impede the surface wind speeds to the same extent as surfaces that have obstacles (such as trees, large buildings and steep hills). The frictional properties of the surface (land or water) can be characterized by a roughness length (for the logarithmic relation) or a wind shear exponent, for the simpler exponential relation. Larger wind shear exponents and roughness length values are present for surfaces with greater wind flow resistance.

The relation between wind speed an the height above a surface is determined using the following two formula:

Logarithmic Relation:

$$\frac{u_2}{u_1} = \frac{\ln(z_2/z_0)}{\ln(z_1/z_0)} \qquad (1)$$

Exponential Relation:

$$\frac{u_2}{u_1} = \left(\frac{z_2}{z_1}\right)^a \qquad (2)$$

In these two formulae, u_2 is the wind velocity at height z_2, u_1 is the wind velocity at a height z_1, z_0 is the roughness length and a is the wind shear exponent. The value of the exponent a is often given as 0.143 for relatively smooth surfaces, and this is known as the "one-seventh law", or the height ratio raised to the one-seventh power. When this actually is the case, the roughness length has a value of 2.5 cm, or 0.025 meter for a 90 meter hub height and a 10 meter reference height. A roughness length of 0.001 meter for the same 90/10 meter arrangement would lead to a wind shear exponent of 0.0972.

In most instances, wind speed measurements are not necessarily conducted at the turbine hub heights, which vary between 50 to 80 meters in this country, and 50 to 124 meters in Europe. In many other cases, years of wind data may exist which have been obtained at or similar to the standard reference height of 10 meters (for land) or 5 meters (for offshore buoys). The wind speed at the potential hub height would need to be estimated from the wind speeds which have been recorded at these other heights. Measurements at two or more height values at the same location can be used to directly calculate the wind shear exponent and the roughness length. The wind speed at the hub height can then be calculated using equation (1) or (2). If only one height value exists, but the wind shear exponent and/or roughness can be estimated, then the lower level wind speeds can be extrapolated to yield the hub height wind speeds. Since wind speeds have a seasonal variation in the Great Lakes region, accumulating data for at least one year is important. Additionally, average yearly wind speeds also vary somewhat, usually by about +/- 6 %, so this information is also important. Ideally, a nearby existing wind speed monitor, even if it is set at a less than optimal height, can be used to correlate the new wind data to the long term wind data. Finally, the distribution of the winds can vary from place to place; different wind speed distributions with the same average wind speed will result in differing energy productions, even for identical turbine configurations.

Usually, roughness length values over water bodies are lower than wind the roughness length values that are observed over land. For water surfaces, a roughness length of 0.001 meter is often cited, which works out to a wind shear exponent of 0.10. However, this low value only applies to smooth water surfaces, which only apply when either the water body is small and/or when wind speeds are slow. As the wind speeds increase, the water surface tends to become more turbulent/less smooth, as waves get larger. Obviously, a lake surface with turbulent “whitecaps” and large waves should have a greater roughness length than a perfectly smooth water surface, although this relationship can be difficult to determine. On large bodies of water, such as the Great Lakes, large waves can form when sustained winds are very fast. For example, some of the highest waves on Lake Erie (near Port Colborne, Ontario) were recorded in the Fall of 2003, at over 16.5 feet averaged over a one hour period in 50 to 70 mph winds.

There have been some attempts to correlate the roughness lengths of water surfaces as a function of wind speed, such as in the paper by D.T. Tsahalis (Journal of Physical Oceanography, 1979, pg 1243-1257). In addition, the recent surge in offshore wind turbine activity in Europe has been preceded by several years of intensive study and monitoring of the wind speeds and wind characteristics at prospective offshore wind farm locations. The wind monitoring at these sites has been conducted with tall offshore wind monitoring towers that measure the wind speeds at several different heights. The wind shear values (roughness length) can be empirically calculated from this real wind data.
A recently published article (Wind Energy, 2003; 6:405-412) describes the wind monitoring near Skegness, Great Britain, where wind speeds were measured at 17 and 43 meter heights, and the average roughness length was 4.7 mm, or approximately 0.005

meter. While this may sound trifling, the greater roughness measurement would yield approximately 10 % extra power versus a water surface of roughness of 1 mm.

Once the wind speeds at known locations have been computed and adjusted to the hub height of the turbine, the energy production of a wind turbine can be computed. This calculation is accomplished with the wind performance curve of the particular turbine, which is usually provided by the turbine manufacturer after being independently verified. Various turbines are designed for differing wind speeds, and while some are more efficient at a given wind speed, they may also be more costly. Since the wind turbine industry is still somewhat competitive worldwide, the manufacturers have found that differing models are better suited to certain wind regimes, and they market their products accordingly, attempting to carve out profitable niches in this worldwide market. In many cases, the turbines can be customized to some extent, usually by the tower height.

THE GREAT LAKES WIND POWER RESOURCE

Once the average wind speeds have been computed for a given area, the amount of recoverable energy per turbine can be estimated. However, due to a phenomena known as wind shadow, wind turbines must be properly spaced far enough apart so that the upwind turbine does not "steal" too much of the downstream turbine's wind energy. This becomes a complicated calculation and an economic optimization problem – how many turbines (of a given turbine size) can be packed into a given area before the wind shadow effect becomes so pronounced that the downstream turbine performance is significantly affecting the energy production (and hence revenues) of the wind turbine array. For offshore wind turbines, a close packing of wind turbines is important, due to the very high cost of high power underwater electric transmission lines. One of the known large offshore wind turbine arrays uses 80 meter rotors; the turbines are 0.5 kilometers (km) apart, or 6.25 rotor diameters (see Figure 1). The Horns Rev arrays is set up in a square pattern (0.5 km x 0.5 km) but in an overall rectangular arrangement of 80 x 2 MW turbines are placed over a 20 km^2 area in an 8 x 10 arrangement. Using this example as a basis for calculating the Great Lakes potential, the turbine density would be 4 turbines per km^2. Unfortunately, this particular type of turbine cannot be sold in this country at the present time due to a patent dispute. In Table 5, the estimated array sizes for given wind turbines, and the resulting turbine density is calculated. With one exception (the 2 MW Vestas V80), only those turbines that can be sold in the U.S. are listed.

Table 5
Wind Turbine Densities at a 6.5 Rotor Diameter Spacing

Turbine Type	Rotor Meters	Capacity MW	Turbine Density per km^2 *	PowerDensity MW/km^2 **
Vestas V80	80 m	1.8 MW	4	7.2
Vestas V80	80	2 MW	4	8
Vestas V90	90	3 MW	3.16	9.48
Bonus 2.3	82.4	2.3 MW	3.77	8.67
Bonus 2.0	76	2.0 MW	4.43	8.87
NEG-Micon NM72	72	2.0 MW	4.93	9.88
NEG-Micon NM82	82	1.65 MW	3.81	6.28
GE 1.5s	70	1.5 MW	5.22	7.83
GE 3.6	104	3.6 MW	2.37	8.52

* Based upon an 8 x 10 turbine array of 80 turbines (same as Horns Rev)

** Refers to MW of capacity, and not necessarily the actual output for actual average speeds. To obtain the actual output, this value must be multiplied by the efficiency of the turbine at the given wind speed at the hub height (for example, 36 % at 7 m/s).

The turbine array will produce less energy per turbine than will an isolated turbine (or one with at least 10 rotor diameters distance between each turbine). The array efficiency is found by comparing the energy output per turbine of the array to the energy than would be obtained by an identical, isolated turbine experiencing the same wind resource. The array efficiency is very difficult to estimate a priori, and is a function of wind direction, array layout, surface roughness and the turbine hub height/rotor diameter. The estimated array efficiency of one of the two large Danish offshore arrays (Horns Rev), which has a capacity of 160 MW, is about 80 % (see Appendix A1) with inter-turbine distances varying between minimums of 6.25 to 8.8 rotor diameters, depending upon the wind direction. (Note: The Horns Rev wind farm estimated the average turbine output to be approximately 7500 MW-hr/yr, and with an 78 % array efficiency the individual "lone turbine" output would be 9512 MW-hr/yr. The V80 turbines would produce this energy from a 9.6 m/s average wind speed. The reported wind speed was 9.51 m/s at 62 meters. http://www.hornsrev.dk). In regions with a strongly directional wind source (such as Buffalo, NY, where 85 % of the available wind energy comes from the southwest quadrant), array efficiencies can be higher than for "omni-directional winds" with proper alignment of the array.

The actual wind turbine output is found by calculating the turbine efficiency at the given average wind speed and multiplying this by the turbine capacity. The results can sometimes be surprising; for example, the NEG-Micon NM82 machine has a lower rated capacity than the NM72 unit, but at moderate wind speeds, the NM82 actually produces more energy than the NM72. The 72 meter unit is designed for faster winds, so that more energy is produced from a smaller blade swept area, which is a circle the size of the rotor diameter.

PUTTING IT ALL TOGETHER – THE GREAT LAKES POWER POTENTIAL

Estimating the Great Lakes wind turbine electrical power potential involves dealing with a number of uncertainties in the calculations. The data with the least uncertainties are the lake areas with suitable depths, and the wind turbine energy outputs as a function of wind speed. The array efficiency is reasonably accurate, although this may also decrease for huge "wind mega-farms". However, the wind speed estimates at 10 meters and the average roughness length contain the largest sources of error, and both must be used to estimate average wind speed at hub height.

Another considerable uncertainty concerns that actual lake areas that could have wind turbines installed in them. In many ways, this is a political decision. With the exception of Lake St. Clair, all of the lakes have commercial grade wind resources, but these vary from lake to lake, and also would probably vary from location to location. For example, winds near Buffalo are probably faster on average than the winds that are near the shoreline at Toledo. This is because the prevailing west southwesterly winds have a 400 kilometer fetch of Lake Erie water and/or ice to move across with minimal resistance, a situation which accentuates the wind resource in the Buffalo Harbor. Turbines located in the western end of Lake Erie would experience slower winds, since these winds have had to move over land and obstacles with higher surface friction before encountering the turbines. It can take several miles of lake fetch before wind speeds approach the low surface friction wind profile.

One of the greatest advantages that the Great Lakes posses as far as wind turbines is concerned lies in the presence of the existing regional electrical grid and the huge population centers located along the shore at places like Buffalo, Cleveland, Rochester and Toronto. Lakes Erie, Ontario, Huron and Michigan are largely surrounded by sets of high capacity electrical transmission lines (see Figure 4), which connect the urban centers with electrical generating complexes such as Niagara Falls (with a combined rated output of 4.8 GW). Numerous thermal power plants have been located along the lakeshore to take advantage of the tremendous cooling capacity of the often ice cold lakes. These electrical transmission lines also can be employed by offshore wind turbines at relatively little added expense. The urban centers also provide a market for this electricity, which makes wind power generated in the region more valuable than wind power generated in Montana or Wyoming. Those states are often at least 1000 miles away from significant markets for the electricity, such as the Chicago and Detroit metropolitan areas, each with a population of over 6 million people.

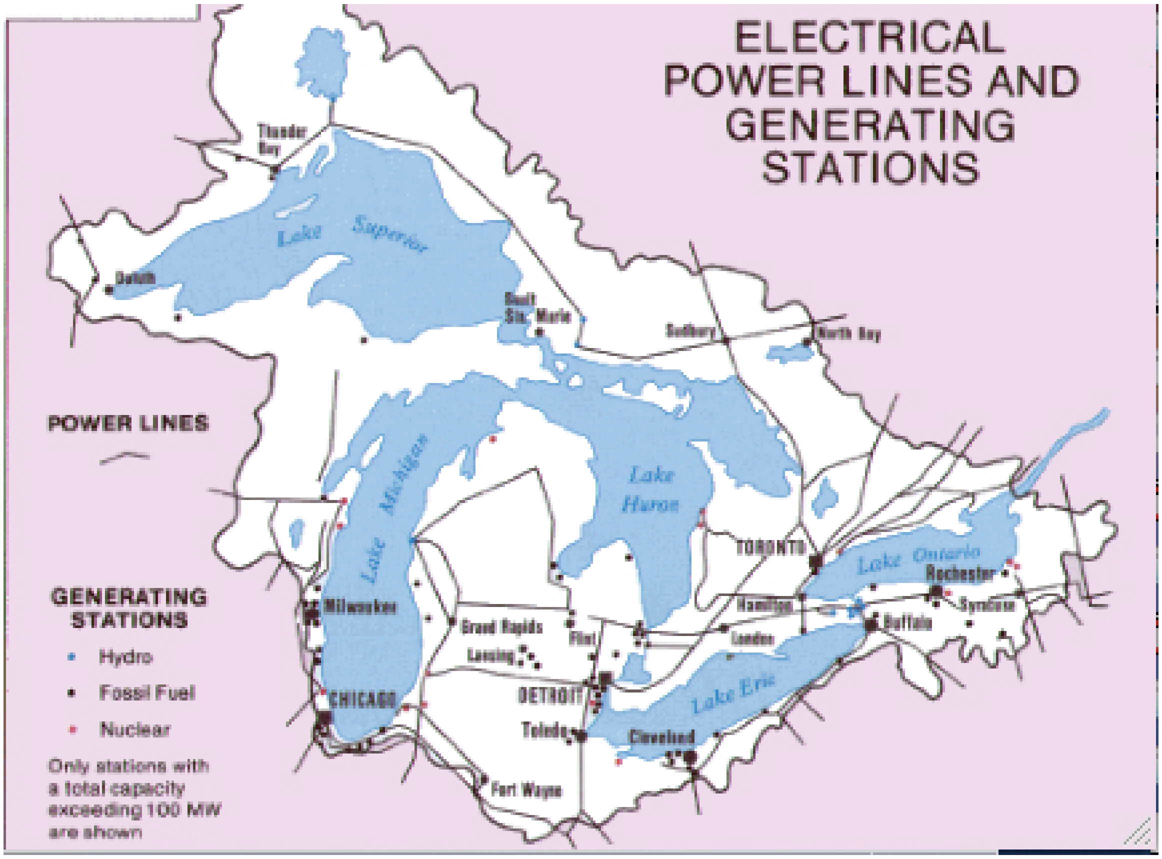

Figure 3
Great Lakes Electrical Overview Map
Source: EPA

RESULTS

In this example, one variety of wind turbine has been selected to calculate the Great Lakes potential power output. This is the Bonus 2.3 MW turbine (see Table 2a), which is a dual speed wind turbine that does not employ the variable speed arrangement. The Bonus performance is easily computed using the wind power calculator in the web site http://www.windpower.org/en/tour/wres/pow/index.htm as a function of air temperature, altitude, wind characteristics, site surface friction and wind velocity. The tower size would be arranged as 90 meters above the water surface (80 meters for the tower and 10 meters for the transition piece). This turbine is employed at the large Nysted wind farm.

In all probability, a combination of wind turbines would actually maximize the energy potential of the Great Lakes. For example, the low wind speed NM82 turbine would be very well suited to Lake St. Clair, since this has the weakest wind resource of any of the lakes. The very large Vestas V90 or the GE 3.6 MW unit might be well suited to the eastern shores of Lake Superior and Lake Huron, since wind speeds are much greater in these areas. Both of these machines were designed for the North Sea, where average wind speeds at turbine hub height are between 8 to 11 m/s.

MAXIMUM TURBINE CAPACITY

For turbines installed in the 0 to 20 meter range, a total of 52,969 km^2 of lake is potentially available. If a 95 % maximum utilization of offshore area is assumed to be available for wind turbine installation, based on Table 3, about 50,000 km^2 would be able to contain 188,500 Bonus 2.3 MW wind turbines with a 6.5 rotor diameter distance between them. The rated capacity per km^2 is 8.67/km^2 with 3.77 turbines per km^2, for a total capacity of 433 GW. The added capacities for the deeper waters are 174 GW (20 to 30 m deep) and 118 GW for the 30-40 m depths, giving a total of 725 GW for the maximum wind turbine capacity of the Great Lakes. The average delivered amount of power would be the efficiency of the turbines (a function of the wind speed) multiplied by the array efficiency (assumed to be 0.8). The key parameter is the wind speed at the hub height, which can be derived from the wind speed at a 10 meter height (Table 3) for each lake, and an assumed roughness length.

In Table 6a, the roughness length of 0.005 meter is employed, which is the value of the offshore conditions measured in the Irish Sea at Skegness, while in Table 6b, a roughness length of 0.001 meter has been used. There is a 6 % difference in the yearly energy output between the two scenarios using a 90 meter hub height, simply as a consequence of using differing roughness length values.

Table 6a
Great Lakes Yearly Energy Output in Offshore Turbine Arrays

Lake	Av Wind Speed 10 m	90 m	Energy /year MW-hr/yr	% Output 100% → 80 %		Array Output kw/turbine*
Ontario	6.42	8.1	8247	40.9 →	32.7	753
Erie	6.68	8.3	8461	42.7	34.1	785
St. Clair	5.5	6.9	6217	30.8	24.7	567
Huron, av	7.50	9.6	10191	50.5	40.4	930
Michigan	6.01	7.7	7368	36.6	29.3	674
Superior, av	6.86	8.8	9162	45.4	36.3	836

Basis: Bonus 2.3 MW turbine, 90 m hub height, Roughness Length 0.005 meter

Table 6b
Great Lakes Yearly Energy Output in Offshore Turbine Arrays

Lake	Av Wind Speed 10 m	90 m	Energy /year MW-hr/yr	% Output 100% →	80 %	Array Output kw/turbine*
Ontario	6.42	8.0	7782	38.6 →	30.9	710
Erie	6.63	8.2	8078	40.1	32.1	737
St. Clair	5.5	6.8	5756	28.5	22.8	526
Huron, av	7.50	9.3	9699	48.1	38.4	885
Michigan	6.01	7.4	6844	33.9	27.2	625
Superior, av	6.86	8.5	8370	41.5	3.2	764

Basis: Bonus 2.3 MW turbine, 90 m hub height, Roughness Length 0.001 meter

The average power output is shown graphically in Figure 4, where the predicted average power output of a Bonus 2.3 MW wind turbine is shown for each lake, using the data form Table 6a.

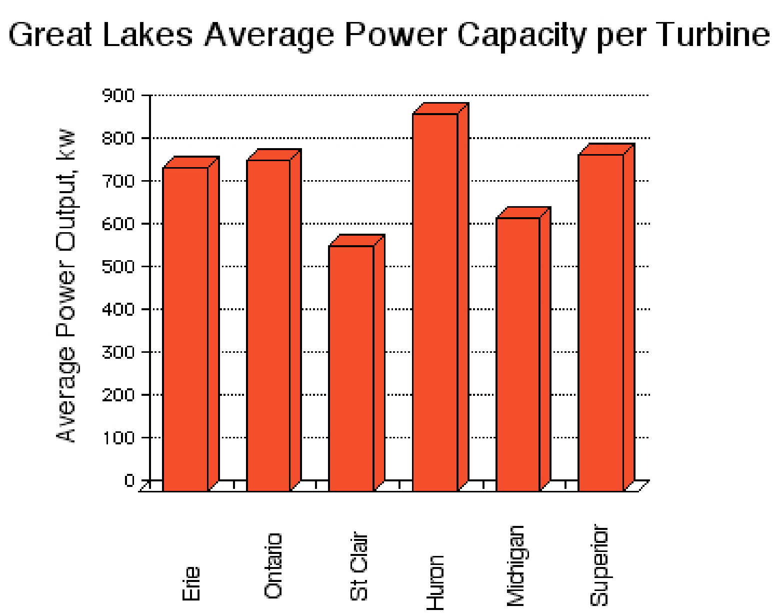

Figure 4
Average Wind Turbine Power Output per Turbine
Bonus 2.3 MW turbines with 90 m towers, in array with 80 % Efficiency

The estimated total power for the lakes is easily obtained by combining the data in Table 6a (energy output per turbine), Table 5 (turbines per km^2) and Table 4 (available area for various depths). In this case, the usable area has been adjusted to 95 % of the maximum area, to take into account shipping lanes and other possible multiple use zones. A depth range of 0 to 20 meters has been chosen for Table 7a, and an average turbine density of 3.77 per square kilometer is employed. The energy outputs correspond to an average roughness length of 0.005 meter. The maximum power outputs for each lake are then computed (Table 7a). This process is repeated for turbines that could be installed in deeper waters in Table 7b (20 to 30 meter depths) and 7c (30 to 40 meter depths), where 95 % of the shallow surface is assumed available for offshore wind farm installations.

Table 7a
Offshore Wind Turbine Electrical Power Output for Great Lakes –1

Lake	Usable Area (95 %) km^2	# Turbines	Unit Power kw	Av Power per lake GW
Ontario	2,595	9,783	753	7.367
Erie	14,904	56,188	785	44.101
St. Clair	1,000	3,770	567	2.138
Huron	14,144	53,323	930	49.589
Michigan	11,567	43,608	674	29.392
Superior	5,787	21,817	836	18.239
Totals	49,997	188,489		150.826

These are staggering amounts of electrical energy, of over 150 GW average continuous power, with an average efficiency of nearly 34.7 %, or 797 kw per turbine, for this particular Bonus wind turbine. The total power output is greater than all the electrical energy production of the Great Lakes states coastal regions and Canada, combined.

Table 7b
Offshore Wind Turbine Electrical Power Output for Great Lakes -2

Lake	Usable Area, 20-30 m km^2	# Turbines	Unit Power kw	Av Power per lake GW
Ontario	1,189	4,482	753	3.371
Erie	7,114	26,820	785	21.050
Huron	4,340	16,362	930	15.216
Michigan	4,381	17,387	674	11.277
Superior	2,071	8,219	836	6.485
Totals	19,095	73,270		58.235

While this amount is certainly not as great as estimated in Table 7a, an average delivered output of 58 GW is still a significant quantity of electricity. The installation costs would be slightly higher than for those located near shallower parts of the lakes due to the added expense of additional underwater cabling. One advantage of the deeper approach is that fewer people might be able to view them, and winds further offshore are likely to be slightly faster than at locations closer to land.

Table 7c
Offshore Wind Turbine Electrical Power Output for Great Lakes -3

Lake	Usable Area, 30-40 m km^2	# Turbines	Unit Power kw	Av Power per lake GW
Ontario	1,140	4,298	753	3.236
Erie	1,030	3,883	785	3.048
Huron	5,244	19,770	930	18.386
Michigan	2,939	11,080	674	7.468
Superior	2,564	9,666	836	8.081
Totals	12,917	48,697		40.219

The total potential electrical power obtainable from the Great lakes via present day wind turbines would be nearly 249 GW average continuous electrical output. As wind turbine technology progresses, even larger turbine placed upon taller towers will be able to tap the winds present at greater heights above the water. There may also be effects known as “nocturnal jets” over the lakes, which would provide much faster wind speeds than those predicted by the logarithmic function (equation 1).

The combined potential wind turbine output for the Great Lakes is given in Table 7d for the depth range of 0 to 40 meters.

Table 7d
Combined Offshore Wind Turbine Electrical Power Output for Great Lakes

Lake	Usable Area (95 %) km^2	# Turbines	Unit Power kw	Unit Power MW/km^2	Average Power GW
Ontario	4,924	18,563	755	2.838	13.978
Erie	23,048	86,891	772	2.959	68.203
St. Clair	1,000	3,770	576	2.138	2.137
Huron	23,728	89,455	883	3.506	83.192
Michigan	18,887	71,204	640	2.541	48.579
Superior	10,422	39,291	789	3.152	33.191
Totals	82,009	309,174			249.280

DISCUSSION

OFFSHORE WIND TURBINE COSTS AND PROFITABILITY

Computing the cost of this wind power can be difficult, because one of the key parameters is the cost of the money used for installing the offshore turbines. The capital portion of offshore wind turbine electrical production costs would be 85 to 90 % of the total expenses, dwarfing the maintenance and insurance costs for these turbines. The installation costs for offshore turbine arrays is also a function of their distance from the shore and the size of the array. Minimizing shoreline distances lowers the installation costs of the high voltage (more than 100,000 volts), high power transmission lines. These underwater cables are very expensive, but are needed to send the collected outputs of many turbines to the high capacity transmission lines on land. When large arrays are installed, the unit installation costs can be minimized in a variety of manners. The capital costs may be lowered by “borrowing in bulk”. In addition, purchasing large quantities of wind turbines would lower the unit turbine purchase price. The proposed offshore arrays near Germany will cost nearly $ 1 billion per wind farm, and the economic viability of these projects is predicated on economies of scale for very large numbers of huge turbines installed in waters up to 40 meters deep and over 50 km from land.

A simplified example production cost is provided for the Bonus 2.3 MW wind turbine array installed on Lake Erie, where the average yearly energy production per turbine in a 6.25 x 6.25 rotor diameter (80 %) array would be 6881 MW-hr. The capital cost is assumed to be 5 % per year over a 25 year time period, with the installed turbine cost averaging $ 2.875 million each. The yearly insurance cost would be $10,050, and the annual maintenance cost would be $24,150, for a total of $ 34,200 (based on published examples). The yearly capital cost (principal and interest) would be $203,990, and the total yearly expense would equal $ 238,190. The average electrical production cost would be the yearly expenses divided by the annual energy output, which equals $34.62/MW-hr, or very close to 3.46 cents per kw-hr. Additional costs would be any taxes paid to localities, states, provinces and federal governments, as well as the profits required if this enterprise was owned and operated by a non-governmental agency. For example, if this electricity could be sold at 5 cents per kw-hr, and taxes/royalties averaged 0.4 cents/kw-hr, the internal rate of return (IRR) would be 8.5 %. When lower interest rates (4.5 %, for instance) are considered over a longer time length (30 years), the production cost would drop to 3.02 cents/kw-hr. If Lake Erie was "maxed out" at 86,891 turbines, the governmental revenues would be nearly $2.57 billion per year using the tax revenue value of 0.4 cents/kw-hr. As a point of reference, the bulk electrical production price (which does not include taxes or distribution costs) charged to Niagara Mohawk customers in 2003 was 5.987 cents/kw-hr. If the wind derived electricity was sold at that rate, the IRR would be nearly 12.4 % using the 5 %, 25 year term capital cost.

Two of the offshore wind farms in Europe also provide a basis for estimating the electrical production costs – the Middelgrunden Wind Turbine Cooperative and the Horns Rev wind farm. The Middelgrunden enterprise (http://www.middlegrunden.dk/) was installed in 2000-2001, when the dollar and Euro were roughly equivalent in value. The 20 turbine, 40 MW enterprise is located 3 km from the shore, and cost E 44 million to build. Based on average wind speeds of 7.2 m/s at hub height, the expected annual output was 4450 to 5000 MW-hr per turbine, or an average of 507 to 570 kw continuous, for a capacity utilization of 25 to 27 %, at an array efficiency of about 80 %. The actual performance has been slightly better than expected, and the electrical production cost has been 4.6 cents/kw-hr, before taxes, but including the investor return.

The Horns Rev wind farm cost approximately 270 Euro to build, which is about E 3.375 per turbine. However, included in the project several tens of millions for ecological research studies on the aquatic and avian wildlife at this site, which is on a major bird "flyway" between the Atlantic/Artic coast and North Africa. The expected average turbine output is 7500 MW-hr. Using a 25 year lifetime and a 5 % interest rate, the production cost would be near 3.59 cents /kw-hr, before any taxes or investor return.

Obviously, there are a number of variables that have significant effects on the electrical production cost. For example, the lowest cost power could be produced with government ownership (such as the New York State Power Authority), since it has access to the lowest cost capital (tax exempt bonds), and the need for profit is theoretically not present. In addition, state and local taxes would not have to be paid, although some arrangement might need to remedy the "Niagara Effect" of probable long term economic blight on local communities. The term of the bonds also has an effect on the interest and principal payments. For private concerns, the income stream would tend to increase over time while costs remain fairly constant, as long as the price of energy steadily increases, thus providing higher profit rates over time for a given investment. The U.S. Energy Information Agency (EIA, http://www.eia.doe.gov/) usually assumes that energy costs will rise at a 3 % annual rate, but electricity prices (largely a result of deregulation) have risen over 10 % per year for the last two years. Thus, at a steady 3 % annual electrical price rise, the IRR of this project could increase from 12.4 % (at 2003 electrical rates) to 25.35 % in 20 years, when the expected electrical price would be 10.8 cents/kw-hr. In addition, once the turbine was paid off, almost all of the income would be profit.

REPLACING POLLUTING ELECTRICAL POWER SOURCES

According the U. S. Dept of Energy and Ontario Power, the areas near the Great Lakes currently have an electrical generating capacity of nearly 75 GW (see Table 8). The U.S. portion of the region, the 8 states that border the lakes have a total electrical generating capacity of near 202 GW; about one third of the combined capacity is located near within "one county" of the lakes. The U.S. portion of the 75 GW amount is obtained by adding up the capacities of thermal (coal, nuclear, oil or natural gas fired) power plants located in a county that borders directly on the lakes or the St. Marys, St.Clair, Detroit, Niagara or St. Lawrence Rivers. Out of the 76 GW, fossil fueled plants comprise 49.5 GW of capacity and nuclear plants comprise 26.5 GW. Only 20 GW of the nuclear capacity is presently operational, and those are only active for an average of about 80 % of the time, due to refueling operations. Most of these thermal plants are not used for cogeneration operations, so the overall thermodynamic efficiency will vary between 35 % to 50 %, depending if they are single cycle or combined cycle, which is the more efficient of the two methods. The power produced by these plants would be less than 63 GW, as many of the plants are not operated at their maximum capacity for various reasons. Some of these reasons are regulatory in nature (such as the Huntley plant on the Niagara River, which sold a portion of its sulfur pollution credits), while others are more economic in nature (such as the Sithe Energy plant in Oswego, which was used in 2002 for less than 50 % of its rated capacity due to the high cost of natural gas fuel). In addition, some facilities are shut down for maintenance for intermittent periods, while others are used largely to supply peaking power requirements.

With the exception of Michigan and Ontario, the majority of electrical power production in the Great Lakes states takes place at thermal power plants that are located at least one county length away from the Great Lakes. The Great Lakes hydroelectric production occurs at the St. Mary's River, Niagara Falls and on the St. Lawrence River, amounting to an average of ~ 5 GW net power production. There are two large pumped hydroelectric energy storage facilities on the Great Lakes – at Niagara Falls (U.S. and Canada) and near Ludington, Michigan with a combined potential of near 20 GW-hr.

The most obvious use of any wind generated electricity would be to distribute it onto the electrical grid, and sell this power directly to customers. One of the advantages of wind turbines dispersed over a wide area is the reliability factor. At any particular location, the wind speeds will vary with time, and exclusive reliance on local wind turbines would result in frequent times of little or no power production, and smaller periods when an overabundance of electricity would be produced. However, by dispersing turbines over a wide area, such as the length and breadth of the Great Lakes, the overall production rate would tend to average out. This problem has been studied by the U.S. Department of Energy by Justus and Hargraves, (RLO/2439-77/2, issued 1978). They found that the average daily variation in wind speed tracked the electrical demand, which means that less peaking power units need to be deployed across the grid. They also analyzed the spatial cross correlation as a function of distance between locations, which relates the probability that the wind speed at one point is related to the wind speed at another point at any particular time. The average cross correlation varied from near 0.6 at a 200 km distance, to near 0.4 at 400 km (which is the distance between Toledo and Buffalo), to 0.25 at an 800 km distance.

Table 8
Presently Installed Great Lakes Near Shore Thermal Electricity Sources

State/Province	Fossil fueled MW	Nuclear* MW	Totals MW
Ontario	7519	13860	21379
New York	6753	3258	10011
Pennsylvania	136	----	136
Ohio	4172	2177	6351
Michigan	17124	4250	21374
Indiana	4154	----	4154
Illinois	3135	1700	4835
Wisconsin	5733	1533	7266
Minnesota	630	----	630
Totals	49356	25178	76134

* Includes ~ 6500 MW mothballed and 950 MW indefinitely closed (safety issues)

If wind turbines were used to provide the majority of the electricity in the Great lakes region, there would probably always need to be a buffer of stored electrical power, where excess power could be stashed for use during times of lower wind speeds. Pumped hydroelectric arrangements seem to be the most energy efficient means of undertaking this goal on a large scale. In Figure 5, a simplified relief map of the Great Lakes region is shown. There are large areas where a 100 meter or more height difference between the lakes and nearby land areas are in close proximity, especially in northern Minnesota, northern Wisconsin, western/central Upper Michigan, as well as near the Owen Sound part of Ontario, the eastern shores of Lake Superior, as well as northeastern Ohio and western New York/Pennsylvania coastline. In addition, New York Sate has several Finger Lakes locations where such schemes would be ideally suited.

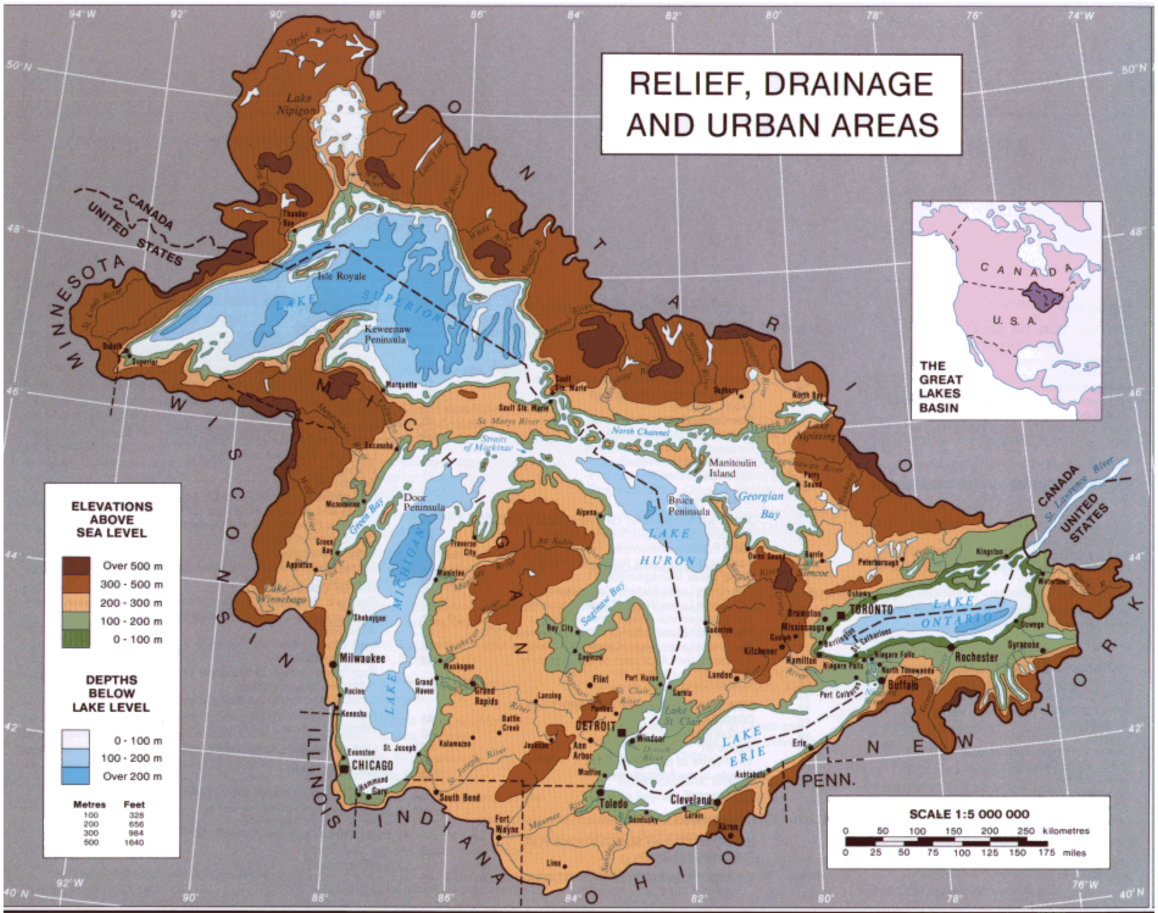

Figure 5
Great Lakes Basin Relief Map (source: EPA website)

OTHER ENERGY USES FOR GREAT LAKES WINDPOWER

The maximum electrical production capability for the Great Lakes appears to be larger than the current near shore thermal power plant capacity, by at least a factor of four. Thus, the Great Lakes have the potential to supply almost half of the combined U.S. and Canadian electrical demand, which is approximately 500 GW average consumption from approximately 1000 GW of electrical generating capacity. The combined land and water based turbine capacity is over 70 % of the combined U.S. and Canadian total. Obviously, due to distance considerations, supplying half of the U.S. and Canadian electricity from Great Lakes wind turbines could not be done efficiently, simply due to power transmission losses. Powering the south and east coasts of the U.S. from the Great Lakes would pose the same difficulties as exist in the Dakotas, which have a combined wind turbine potential of at least 240 GW. Despite all of this potential "Dakota power", there remains the problem how to send this huge amount of energy to markets for this electrical power, such as Chicago, Detroit, Cleveland, Philadelphia and New York City, especially if such electrical energy could be produced in the Great Lakes for similar delivered costs.

Economically speaking, this would require comparing the more expensive offshore wind turbines tied into the existing electrical grid versus the less expensive onshore turbines, which would require long distance, high capacity transmission lines. There would also be intense political ramifications concerning where the huge turbine investment would take place, which would translate into where would job creation occur and wealth would accrue.

Some of the potential Great Lakes wind derived electricity could be employed in the production of biomass fuels. This includes ethanol, methanol, higher alcohols and "bio-diesel", which are often esters of fatty acids from crops such as soybeans and canola. These liquid fuels are readily used in transportation applications, especially as substitutes for gasoline and diesel, with minimal, if any, modifications required for existing cars, trucks, tractors, boats and ships. In addition, these fuels can be used for powering "peaking units" in backup electrical generators, or at locations not easily connected to the grid or with pumped hydropower capability. This approach uses a renewable energy source (wind) to produce electricity that can be used to help grow fuel crops, and to process those crops into liquid energy fuels that can replace non-renewable fuels such as gasoline and diesel fuel. Such an arrangement would also not significantly contribute to global warming, and would help improve the national economy by lowering the export of money to pay for imported oil and oil products.

This approach is based upon the conversion of some of the wind turbine generated electricity into hydrogen, but it generally would not require the installation of an extremely expensive "hydrogen infrastructure" for distribution, storage and/or consumption of this hydrogen. Instead, the hydrogen would be used to produce ammonia and to reduce carbon dioxide into alcohols and methane. Ammonia (NH3) is used as a fertilizer for crops, in the form of urea, ammonia, ammonium sulfate, ammonium phosphate and ammonium nitrate. The wind turbine produced hydrogen could avoid the use of up to 5 % of the U.S. natural gas consumption used for NH_3 production, since all synthetic NH_3 made in this country is made using natural gas as the hydrogen feedstock. Wind turbine electricity could also be used in the production of ethanol, other alcohols and chemicals (powering motors, lights, process equipment, heat pumps, vacuum pumps, etc), displacing electricity formerly produced via fossil fuels, as well as some or all of the process heating requirements. Some hydrogen could also be employed to directly produce methanol and/or ethanol by the reduction of carbon dioxide, which can readily be obtained from fermentation processes. Some of the bio-fuel compounds could also substitute for compounds presently made with petroleum, as either intermediates or products. One of the by-products of the reduction of carbon dioxide is methane, which has considerable use for heating, and is the main component in natural gas. In addition, the byproduct oxygen from the hydrogen production would need to be effectively utilized and/or sold, to keep the overall production costs at a more reasonable level.

HYDROGEN PRODUCTION

At the present time, about 95 % of all hydrogen made in the U.S. is made by either "cracking" hydrocarbons, partial oxidation of hydrocarbons or by steam reforming of natural gas or coal. Electrolysis of water (hydrogen and oxygen) or brine solutions (hydrogen and chlorine) provides the remainder of U.S. produced hydrogen. The electrolysis of water has been conducted commercially for over 80 years, and the technology is very well defined. Commercial units are sold with capacities of a few kilowatts to several hundred kilowatts per electrolytic cell, and some plants operated with very high production rates using multiple cells. Norsk Hydro, a very large Norwegian oil, gas, power and chemicals producer has operated ammonia plants for over 60 years in Norway, which were supplied by electrolytic hydrogen made using very inexpensive hydroelectricity. The plants were converted to natural gas due to a combination of recently discovered natural gas and the interconnection of Norway's power grid to Germany's; the hydroelectricity could be sold more profitability to Germany rather than to be used to make hydrogen. Currently, the electrolytic hydrogen route is used to supply an ammonia plant in Iceland. Often, small H_2 consumers are supplied with electrolysis units rather than obtaining expensive purchased H_2 delivered in a liquid form by trucks. Converting H_2 gas into a cryogenic liquid consumes about 50 % of the energy used to produce the H_2 via electrolysis.

The electrolysis of deionized water produces very pure H_2 and O_2, typically 99.995 % purity, not including water vapor. The cells operate at near 85 % efficiency, so that some cooling must be supplied to keep them at a stable operating temperature. These are continuous production facilities, but production rates can be readily adjusted, especially with modern controls. Eight times more O_2 is produced by weight than H_2. Finding a market for this O_2 is very important in the overall economics of this process; for example, part of the ammonia produced at an ammonia plant could be oxidized into nitric acid, thus consuming the O_2 co-product.

The economics of water electrolysis facilities fall into two basic categories – capital and operating costs. The operating costs are composed almost entirely of the electricity cost, which in this case is the "raw material cost". For a unit that is 85 % efficient in electricity that is priced at 5 cents/kw-hr, the electrical cost would be \$1.06/lb of hydrogen with no credit for the byproduct oxygen. The current market price for oxygen gas (liquid O_2 is approximately twice the price of delivered gas) is \$0.011365/lb, or \$22.73 per ton; sale of the co-product would lower the net hydrogen cost to \$ 0.969/lb.

HYDROGEN GAS FOR HEATING AND COGENERATION

If the problems of bulk hydrogen distribution are solved, such as with new, compatible pipelines, hydrogen could be employed as heating gas, and as a substitute for natural gas. An obvious possibility is for industrial heating uses and cogeneration facilities. The hydrogen could be burned to make steam for heating and/or making electricity followed by heating, or used directly for heating homes and offices, with thermal efficiencies up to 85 % obtainable. This would bring the overall efficiency to 59 % (includes storage, transmission and leakage considerations). The H_2 could be stored in underground structures, just like those used for natural gas. If the H_2 was stored and then used in stand alone generation units where the overall efficiency is near 50 %, the overall system efficiency would drop to near 35 %, which is less than half of the efficiency of pumped hydroelectric storage schemes. Another possibility is to convert residential housing to electric heating, which avoids the conversion losses of electricity to hydrogen to delivered heat.

AMMONIA PRODUCTION

At present, all synthetic ammonia in the U.S. is made from natural gas, steam and air, and its production presently uses about 1.15 trillion cubic feet per year of natural gas. To make ammonia, nitrogen is first separated from air via known mechanical and cryogenic distillation methods. Next, the hydrogen is prepared by steam reforming of methane, which is the main component in natural gas. However, various other hydrocarbons and even coal can be used in variations of these processes. A hydrogen yield of approximately 100 % is obtained by the partial oxidation of methane, but this is somewhat deceptive, as is shown below. The process is very energy intensive (25kcal/gm-mole), and in effect, “mines” hydrogen from the methane while oxidizing the carbon contained in the methane molecule for the energy required by the process. The process involves an extensive cleanup process to remove the impurities and reactants from the H2 product, especially carbon monoxide, carbon dioxide, oxygen and methane.

The overall energy for the process is provided by the combustion of methane:

$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O \qquad (3a)$$

The hydrogen is produced by the water-shift reaction between methane and steam, and then carbon monoxide and steam:

$$CH_4 + H2O \leftrightarrow CO + 3\,H_2 \qquad (3b)$$

$$CO + H2O \leftrightarrow CO2 + H_2 \qquad (3c)$$

The overall reaction is :

$$2\,CH_4 + 2\,H_2O + 2\,O_2 \rightarrow 2\,CO2 + 2\,H_2O + 4\,H_2 \qquad (3d)$$

The net reaction can be simplified from (3c) to become:

$$CH_4 + O_2 \rightarrow CO_2 + 2\,H_2 \qquad (3e)$$

Any carbon monoxide (CO) made in the process must be removed from the H2 stream, as it can contaminate the catalysts used in the ammonia synthesis, or create unwanted impurities during the production process.

Since the net reaction is a partial oxidation of methane, it is very exothermic, and generates most of the energy to power an ammonia plant. However, the reaction of N_2

with H_2 is also exothermic, approximately 10.1 kcal/gram-mole. Cooling for this catalyzed reaction is done with water that is converted to high pressure superheated steam, which in turn drives the compressors needed to make the reactions (especially the NH_3 part) workable. A great deal of the capital infrastructure of an ammonia production plant is tied up in the separation of the H_2 from any CO_2, CO, and O_2 that exits the oxidation reactor.

The NH_3 reaction takes place between 135 atmospheres (KAAP process) to 260 atmospheres (traditional Haber process) of pressure and a temperature of 250 to 500 C. The compression of the reacting gasses can raise their temperature to reacting temperature; some cooling in the initial compression stages will be needed. Usually a combination of 3 staged compressors is required, usually steam driven, to bring the N_2 and H2 reactants to reaction conditions. Given the huge production capacities of most NH_3 plants, the compressors are also huge, with awesome energy (usually high pressure, superheated steam) requirements. The reaction is as follows:

$$N_2 + 3\,H_2 \rightarrow 2\,NH_3 \qquad (3g)$$

The ammonia can be burned with O_2 to produce nitric acid, which can be reacted with ammonia to produce ammonium nitrate (AN); this process also can consume all of the electrolysis by-product, O_2. The AN is a very effective fertilizer and commercial explosive, and millions of tons are produced in the U.S. and Canada every year.

The most advanced processes use two different catalyst beds (KAAP Process). The first one is a hematite impregnated with a potassium salt, with gets converted to potassium-hydride/amide/iron/iron hydride at 300 C and in a high pressure hydrogen atmosphere. The catalyst complexes the molecular nitrogen ("fixes N_2"), which is then reduced to NH_3 by the H_2. The second catalyst bed uses a ruthenium catalyst, which tolerates higher NH_3 concentrations. The yield after the catalyst bed passes is about 20 to 25 %, so recycle of un-reacted N_2 and H_2 is required, but less than in the traditional Haber process. The ammonia is then condensed out of the mixture, and the N_2 and H_2 are recycled. The KAAP process is much more energy efficient than the traditional route.

The NH_3 reaction would benefit enormously from the use a H_2 feedstock that is not contaminated by either O_2, CO_2 or CO, as well as other inert gasses such as argon. However, the preparation of H2 is a very energy intensive operation, and extremely large energy requirements are needed to make large quantities of NH_3. In the conventional coal and natural gas based processes, this energy is obtained by the oxidation of large amounts of carbon obtained from non-renewable (at least for the next several million years) sources in the form of methane, oil or coal.

Since H_2 can also be obtained by the electrolysis of water at an energy yield of approximately 85 %, all that is required is a large scale source of electricity to produce large amounts of H_2. If the electricity source is obtained from renewable, non-polluting sources such as wind turbines, there is no net contribution of carbon dioxide into the atmosphere, so the greenhouse contribution is close to zero. An added complication is that the cost of the electricity must be close to the cost of fossil fuel on a per pound of hydrogen produced basis to produce competitively priced product. This cost can be lowered somewhat via sale or use of the by-product oxygen.

For almost all of the 20th century, the cost of coal, oil and especially natural gas has been very low compared to electricity. These fossil fuels actually have been the preferred energy sources for electricity production, based entirely upon the economics of the process. However, this trend has changed drastically for natural gas and oil, due to the dramatic price rises of these commodities in the last decade. Coal based routes have lost some favor due to some consideration of the greenhouse effect and various air pollutants released by the combustion of large amounts of coal. As of January, 2004, the delivered price of natural gas in the Midwest and northeast U.S. was near $7.50 per MBtu (which is $ 7.19 per thousand standard cubic feet, or $0.1613 per pound of CH_4). According to equation (6e), a mole of methane is converted into 2 moles of hydrogen, which is a mass ratio of 4 lbs CH_4 per lb of H_2. The raw material cost of this H_2 then becomes $ 0.645/lb H2 from the steam reforming of methane.

It requires 68.3 kcal of energy to convert 18 grams of liquid water into 2 grams of H_2 and 16 grams of O_2 gas at 100 % efficiency, which is equivalent to 18.02 kw-hr per lb of H_2. Many of the quoted water electrolysis production rates are for existing large scale commercial alkaline based units, including those made by Norsk Hydro. The efficiency of these cells is generally given as 4.1 to 4.4 kw-hr/m^3 of H_2 from actual plant operating experience; this is equivalent to 20.85 to 22.37 kw-hr/lb H_2, or 86 % to 75 % overall efficiencies, respectively. Several large scale ammonia plants have been operated, almost always in areas with very inexpensive and plentiful hydroelectric supplies and where natural gas is expensive or hard to obtain. The largest such plant in North America was a 75 MW water electrolysis/ammonia plant at Trail, British Columbia. Its production capacity would have been between 150 to 170 million pounds of ammonia per year.

At an average of 85 % efficiency, the conversion factor is 21.2 kw-hr per lb of H_2. The electrical cost at which the steam methane reforming (SMR) process with delivered methane priced at $7.5/MBtu and water electrolysis routes become equivalent is $ 0.0314 per kw-hr, without any credit for the O_2 by-product. If the O_2 by-product (at $25/tonne O_2, or $ 0.0909/lb H_2) is considered, the electrical credit for the O_2 becomes $0.0043 per kw-hr, and the equivalent electrical cost for electrolytic H_2 becomes $ 0.0357/kw-hr, or 3.57 cents/kw-hr. At present, offshore wind turbines will not be able to provide electricity cheaply enough to compete with the present price of natural gas, even if this process does make more sense from a global ecological/climatic point of view. The cost differential is largely a result of the electrical distribution costs, which can be 1 to 2 cents per kw-hr even for large bulk purchasers of electricity, and higher for smaller customers. For example, if wind turbine produced electricity could be delivered to an electrolysis plant at 5 cents per kw-hr, the equivalent delivered natural gas price would be $ 11.93/MBtu without any O_2 credit, or $10.90 per MBtu with the O_2 credit.

The price of both natural gas and oil would have to increase somewhat over their current levels to make the electrolysis route competitive with natural gas, or other actions would need to be taken. At the present delivered price of $7.5/MBtu, the delivered bulk gas price would need to rise by 45 %. Tax credits and other incentives (such as the Production Tax Credit, and/or Green Tags) provided for the wind-generated electricity would have the same effect as lowering the price of manufactured electricity. For example, if offshore electricity was made at a cost of 3.57 cents/kw-hr, and credits of 1.8 cents/kw-hr were provided, the net offshore production cost would be 1.77 cents/kw-hr. If the dedicated distribution price was 1.4 cents per kw-hr, the wind turbine profit was 0.4 cent/kw-hr, the electric cost to the electrolysis plant would be 3.57 cents/kw-hr. The current subsidies provided to natural gas and oil supplies could also be removed (tax deductions and credits, military security services), or the cost of the carbon dioxide by-product (a carbon tax) to society could be factored into fossil fuel sales. Given the current natural gas and oil pricing, a carbon tax of $ 50 per ton of CO_2 emitted would be needed to make the steam reforming cost equivalent to electrolysis done with 5 cent per kw-hr electricity and credit for O_2 at $22.73/ton was obtained. Another remote possibility is a tariff on imported gas and oil, which would have the same effect as raising the price of all oil and gas sold in this country.

The conversion of water, electricity and air into ammonia and oxygen should be significantly less capital intensive than the traditional coal, oil or methane based routes. This is because the separation of H_2 is much simpler in the electrolytic route than from oxidation or water gas "shift" reactions, since removal of water and trace amounts of O2 and inert gasses such as carbon dioxide and argon is all that is required. This would translate into significantly lower capital and operating and maintenance (O & M) costs. The oxygen by-product gas can also be sold, or it can be subsequently employed to oxidize the ammonia into nitric acid.

The capital and operating costs of water electrolysis system have been discussed in some detail in the book "Hydrogen: Production and Marketing" by Smith and Santangelo (American Chemical Society, 1980). In their cost analysis, 81.8 % of the expenses were for raw materials, which, in this case, was almost entirely electricity, while 15 % of expenses were allocated as the return on investment (20 % before taxes). For electricity costing 3 cents/kw-hr, the H_2 product could be produced and priced at $ 0.80 per pound of H_2; at 5 cents/kw-hr for electricity, the H_2 cost would be $1.24/lb. Their study also compared the cost of H_2 made via steam reforming of natural gas, although the delivered gas price was $2/Mbtu. As of January, 2004, the delivered natural gas price was quoted as more than $7.50/MBtu; once this large price increase is factored in, the steam reforming cost would be close to $0.78/lb H_2.

Over the long term, several factors will create more favorable economic conditions for electrolytic H_2 and opposed to H_2 made via steam reforming. For example, as the electricity price rises in response to rising natural gas prices, the cost of O_2 also will increase. Oxygen is normally made as a by-product of nitrogen production, which involves the compression of air to very high pressures, followed by distillation. The energy for this compression is usually provided by electricity, and energy is one of the most significant cost factors in O_2 and N_2 production. However, the most important factors will be the pricing of oil and natural gas, and the value of the dollar relative to more stable currencies, such as the Euro. In 2003, the price of oil in dollars went from near $25 per barrel to $35, largely as a result of the devaluation of the dollar relative to the Euro; the price of oil in Euro's actually has remained somewhat constant. Two other factors affecting the price of oil and natural gas are the world economic activity, and the demand for oil and gas in India and China. These two nations are the world's two most populous countries, and whose economies grew by 7 to 10 % in 2003. The result has been a dramatic stimulus to the world oil and gas demand, and the price of oil and gas has risen in response to the rising demand and relatively constant supply of hydrocarbons.

WIND DERIVED ELECTRICITY USES FOR ETHANOL PRODUCTION

One of the more strident arguments against the use of ethanol for a fuel for automobiles is that ethanol made by fermentation of crops is actually of little, or less than any, utility in reducing net global CO_2 production, or in the reduction of the amount of imported oil needed in transportation. The theory behind this reasoning is that the amount of energy used to grow the crops, harvest the crops, transport them to the fermentation plant, hydrolyze the starches, ferment the sugars, and distill off the ethanol is greater than the amount of energy obtainable from the oxidation of the ethanol. Most of the energy used in these processes is supplied by fossil fuels, such as natural gas for the nitrogenous fertilizer, diesel oil for tractors and transportation, as well as naturals gas or coal for bio-fuel plant operations. This may have been true during the 1980's, but modern facilities have become much more energy efficient, so that the entire process is now "net energy positive", by approximately 20,000 Btu/gallon of ethanol. In addition, the main product of this operation, ethanol, is a form of energy very useful in transportation, and a direct replacement for gasoline. The major byproducts from the fermentation process are also sold (high protein concentrates, CO_2).

A great deal of the fossil fuel inputs for ethanol can actually be replaced with non-polluting wind derived electricity. Three of the most obvious examples of this substitution include the production of ammonia derived fertilizers using wind turbine derived hydrogen, the production of purified nitrogen (used for ammonia synthesis) gas using wind derived electricity, as well as the operation of the fermentation and water treatment plants using wind derived electricity. In the plant operation, the distillation operations can also be conducted with wind derived electricity, using electrically powered heat pumps and partial vacuum distillation conditions keyed to the coolant water temperature that is used as the source of heat for the heat pump. Heat pumps have very high coefficient of performance (COP) values (between 4 to 8) if the temperature difference between the working fluid output temperature and input temperature can be minimized (between 20 to 30 C difference). The distillation at absolute pressures of between 40 to 120 torr also produces ethanol that has a water content of less than 0.5 wt %, as opposed to 5 wt % water when the distillation is conducted at atmospheric (760 torr) pressure. The Great Lakes obviously are very suitable plant locations for such operations, due to the plentiful supply of coolant water, markets for the ethanol, and existing transportation/industrial infrastructure.

HYDROGENATION OF CARBON DIOXIDE

The reaction between carbon dioxide and hydrogen is exothermic, and ranges between 25 to 40 kcal/gram-mole, depending upon the reaction conditions and products of the reactions (up to 42 % of the energy released by burning coal, which is 94 kcal/gm-mole). The hydrogenation reaction can be varied by choice to catalysts and reaction conditions to produce carbon monoxide, methanol, ethanol, methane or other compounds. For example, mixtures of these were reported using a mixed rhodium-iron catalyst (Energy, vol 22, no.2/3, pp. 343-348, 1997). Almost all of these reactions proceed via the carbon monoxide intermediate. The carbon monoxide intermediate can also be used in a variety of applications, such as for intermediates such as phosgene (used to make polycarbonate, most isocyanates), methanol, formaldehyde, formate esters, organic carbonate esters, acetic acid and other high volume chemicals. At the present time, almost all of the methanol made in the U.S. is done via the partial oxidation of methane. Methanol is a very useful compound for chemical synthesis, for use in certain products, and it is also a very useful form of stored chemical energy – a liquid fuel. In New Zealand, it is the key intermediate in the Mobil synthetic gasoline process (methane to methanol to gasoline), as this country used to have plentiful natural gas supplies but no crude oil supplies (it now has neither). Methyl alcohol can also be converted into ethanol by a similar reaction as the gasoline synthesis (also known as homologation). These intermediates can be used to produce a wide variety of other high volume chemicals. For example, ethanol can be converted catalytically into H2 and ethyl acetate; over 1 billion pounds of ethyl acetate are produced in the U.S. each year, almost entirely from hydrocarbons or coal derived compounds. Ethanol can also be converted into ethylene and ethylene oxide; more than 30 million tons of these intermediates are used in the U.S. every year. This would be the equivalent of nearly 27 billion gallons of ethanol annual production. Most ethylene is currently produced by "cracking" ethane or methane, both of which are extracted from natural gas or petroleum.

As long as natural gas is inexpensive relative to H_2 prepared via hydrolysis, the oxidation of methane will be the preferred methanol synthesis route. For example, at the current delivered price for natural gas of \$ 7.5/MBtu, the price of methane is approximately \$ 0.17/lb. The raw material cost for methanol is also very similar to that price (adjusted for the molecular weight difference), since air is very inexpensive, so the raw material price for methanol is near \$ 0.09/lb, or about \$0.61/ gallon of methanol. The actual manufactured price would be more than this due to operating and other financial costs. This is a significant contrast to the use of electrolytic hydrogen and carbon dioxide. For example, if the CO_2 was available at essentially no cost, and H_2 was made at \$ 0.97/lb (from electricity at 5 cents/kw-hr and with the \$25/metric ton O_2 credit), its raw material cost would be near \$ 0.12/lb, or \$0.79/gallon. This value of 12 cents per pound assumes a 100 % yield, which may not be the case in an actual production facility, so the actual cost would be greater than this minimal cost. It is, however, fairly close to the present raw material cost for methanol preparation, and becomes equivalent when the delivered natural gas is priced at \$10.90/MBtu at quantitative yields. In addition, the exothermic reaction takes place at 300 to 400 C, and the cooling of the reaction would produce high pressure superheated steam which could be used to produce additional electricity.

The fuel value of methanol is about half of that of gasoline, while ethanol has a fuel value of 75 % of gasoline, at 77,000 Btu/gallon. Methanol can be difficult to blend with gasoline, since it is a very polar material and has little solubility with hydrocarbons such as octane and decane. If the methanol is converted into ethanol and higher alcohols, the result is a liquid fuel made that has a higher specific energy content, and which is more miscible in gasoline. Another approach to "renewable" methanol made from hydrogen would be its sale as a commodity chemical. This approach would also be a net reduction in the consumption of either natural gas and/or coal into CO_2, where methanol is merely an intermediate:

$$CH_4 + 0.5\ O_2 \rightarrow CH_3OH;\ +\ 1.5\ O_2 \rightarrow CO_2 + H_2O \qquad (4a)$$

If the methanol is made from coal, even greater amounts of carbon dioxide per pound of methanol are made, as energy needs to be provided to undertake the synthesis gas reaction:

$$3C\ + 1.5\ O_2\ +\ 2\ H_2O \rightarrow 2\ CO_2\ +\ CH_3OH \qquad (4b)$$

There is also the possibility of using a combination of electrolytic H2 and carbon monoxide to produce methanol, where the overall net reaction is:

$$C\ + 0.5\ O_2 \rightarrow CO;\ \ + 2\ H_2 \rightarrow CH_3OH \qquad (4c)$$

However, the only "Greenhouse Gas" neutral approach is the use of CO_2 (as a carbon feedstock) that is obtained either from the air or from a process source such as fermentation or wastewater treatment. If the water treatment approach was used, O_2 from the electrolysis of water could be used instead of air for the biological oxidation of wastewater, and the H_2 from the electrolysis could be employed to reduce the CO_2 byproduct from the bacterial oxidation to produce methanol or ethanol fuels.

Carbon dioxide can also be reduced directly to ethanol when different catalysts and process conditions are employed. Several catalyst systems have been described where relatively high ethanol yields have been demonstrated while methane was the other product. For example, an 82.5 % selectivity of CO_2 was described (see Journal of Catalysts, 175, pp. 236-244 (1998)), with the byproducts of carbon monoxide and methane (unknown ratio). In (4d), all of the carbon monoxide is assumed to be eventually fully hydrogenated in a secondary reaction zone.

$$2\ CO_2 + 6.35\ H_2 \rightarrow 0.825\ C_2H_6O + 0.35\ CH_4 + 3.175\ H_2O \qquad (4d)$$

If the price of natural gas was given at \$ 10.90/MBtu, where it is cost-equivalent with electrolytic H_2 made with 5 cent/kw-hr electricity, the methane price becomes \$0.2421/lb. If H_2 at 21.2 kw-hr/lb was made with electricity at 5 cents per kw-hr with an O2 credit of \$ 0.0909/lb of H2, and the CO_2 was provided at no cost, the raw material price of the ethanol made from CO_2 and H_2 would be near \$ 0.29/lb of ethanol. This cost is equivalent to \$1.88 per gallon, which is near the cost of ethanol that is made via fermentation of crops. If improvements could be made to minimize methane formation, the raw material price for the ethanol would drop to near \$1.65 per gallon. The hydrogenation facility should be energy self-sufficient by tapping the considerable heat of reaction (near 40 kcal/gm-mole of ethanol produced).

Factoring in H_2 production, high pressure storage, fuel cell efficiency and electrical motor efficiencies, the fuel cell/H_2 cost could be similar to delivered ethanol, even if electrical motors are vastly more efficient than internal combustion. However, the use of more efficient internal combustion engines/systems would shift the economics to favor the use of ethanol, negating the economic benefits of the H2/fuel cell approach. Several technical issues also must be overcome for the automotive H2/fuel cell approach, such as inexpensive, lightweight, very high pressure gas storage (4500 psi) vessels, low temperature operation, fuel cell lifetime, fuel cell cost, H_2 delivery, the wisdom of widespread high pressure H_2 distribution, as well as the ramifications of large scale hydrogen leakage into the atmosphere. Additionally, the H_2 delivery system does not yet exist, nor do the renewable energy generation sources to make this H_2, so any H_2 made from non-renewable sources could pose significant pollution and global warming problems. Another idea has been to generate H_2 at the site of its use or sale (small electrolysis unit at homes or local service stations, for example). However, the electricity cost would also include the distribution costs for electricity, in effect, doubling the electrical cost, which would double the cost of the hydrogen fuel. Another problem with local H_2 generation is that there is no use of the oxygen byproduct, and this leads to an even more expensive cost for the H_2. Finally, large scale use of H_2 powered fuel cells in cars would mean that internal combustion engines, and those cars with such engines, would become useless, and new cars and trucks would be required. The use of bio-fuels such as ethanol allows the use of existing equipment, which is valued at several trillion dollars.

DISPLACING OIL and GAS

The U.S. currently consumes an average of 17 million barrels of oil per day and about 23 trillion cubic feet of natural gas per year. Over 60 % of the oil is imported, and approximately 25 % of the natural gas is imported (mostly from Canada and Mexico), costing this country nearly \$170 billion/year at current prices of \$35/bbl and \$6.2/MBtu for oil and gas, respectively. Approximately 1.7 million barrels per day (Mbpd) are consumed in oil refineries, and more than 2 Mbpd are consumed by the production of commodity chemicals. The three largest uses for oil are gasoline, diesel fuel and heating fuel. From a global warming perspective, where the oil and natural gas originate is irrelevant, since it is all being burned and the resulting CO_2 is being dumped into the atmosphere.

From an electrical energy view, crop fermentation and resulting distillation of the ethanol can provide a way of producing ethanol from electricity. However, if available electricity exists at a reasonable price, the following overall net reaction is possible, using glucose derived from plants as a starting raw material:

$$C_6H_{12}O_6 + 6.3\ H_2 \rightarrow 2.825\ C_2H_5OH + 0.35\ CH_4 + 3.175\ H_2O \quad (5a)$$

The reaction is 50 % efficient in H2, but the utility could be much greater, since a ready-to-use liquid fuel is produced. This reaction would be in contrast to the traditional fermentation reaction of sugars/hydrolyzed carbohydrates:

$$C_6H_{12}O_6 \rightarrow 2\ C_2H_5OH + 2\ CO_2 \quad (5b)$$

Such a process would increase the yield of ethanol by 42 % per unit of glucose, as well as provide methane byproduct, which can be readily used in heating applications. The ethanol and methane products would also be "greenhouse gas neutral", and would not contribute to the anthropogenic carbon dioxide input into our atmosphere. The ethanol and methane would not require the manufacture of fuel cells or the construction of hydrogen compatible gas pipelines, and can be immediately employed in the existing societal infrastructure if the H_2 was generated on site and the electricity was provided from distant sources.

Based strictly upon heating values, 1 gallon of ethanol is equivalent to 0.75 gallon of gasoline. If the overall conversion of electricity to hydrogen to ethanol (using equation 4d) is 7.1 kw-hr per lb of ethanol, then the amount of electricity required to displace a gallon of gasoline (as ethanol via hydrogenation of carbon dioxide) would be 9.45 kw-hr per lb of gasoline, or roughly 59 kw-hr per gallon of gasoline. This translates into 104kw continuous power to produce a barrel-equivalent of gasoline per day, or 104 GW continuous to produce the rate of ethanol production equal to 1 Mbpd of gasoline via hydrogenation of CO2. The combined fermentation/water electrolysis/carbon dioxide hydrogenation system could produce the equivalent of 3.35 Mbpd gasoline equivalent if 1 Mbpd gasoline equivalent was made from hydrogenation of the CO_2 byproduct. The actual amount of ethanol made per day would be 187 million gallons per day (Mgpd); 56 Mgpd via hydrogenation and 131 Mgpd from fermentation of crops. It would require approximately 142 million acres of cropland, or an area approximately 471 miles square (221,517 square miles). The amount of methane produced would also be considerable, at approximately 1 billion cubic feet per day, or 6.9 % of the current average daily consumption of natural gas.

Modern fermentation of crops utilize both the cellulosic and starch portions of the crops for fermentation; many of the higher value added parts of the plant (proteins, fats and oils) are not required in the fermentation process. These are usually separated and sold separately, often as feed for livestock or incorporated into various food products. If these carbohydrates were fed to livestock, a significant part of this portion of the food would be converted into methane by bacteria in the animals' digestive tracts. This methane is also a contributor to the current global warming situation that humans are imposing onto the planetary ecosystem. At present, approximately 90 % of the major grain and soybean crops produced in this country are fed to livestock, and humans consume less than 10 % of the crops directly.

ALTERNATIVE DIRECT USES of H_2

In recent times, a great deal of publicity has been devoted to the concepts of direct use of hydrogen as a replacement for natural gas, and as a replacement for gasoline. An inordinate amount of attention has also been given to ideas centered around the use of hydrogen as a stored energy medium, especially in various electricity schemes.

Obviously, producing and using electricity directly, without any storage, makes far more sense than producing electricity, converting it into a stored form, and then converting the stored energy back into electrical energy for use. Every transformation of one energy form into another results in certain losses. At present, one of the most efficient electrical storage arrangements are pumped hydroelectric systems, where overall efficiencies are between 65 to 85 %. In contrast, the electrolysis of water is about 85 % efficient, and then energy must be expended to store the H_2, as well as convert it back into electricity.

There are two routes to convert stored H_2 back into electricity – by combustion and by fuel cells. The more efficient combined cycle combustion systems average 50 % efficiencies, although performance to 55 % is possible if cold inlet air and cold water coolant are available. Cogeneration systems can reach 85% efficiencies, where the waste heat from the steam turbines is utilized, but the electrical yield is still between 35 to 50 %. In this country, most existing combined cycle plants do not employ co-generation, as they are stand-alone units with no nearby paying customers for the waste heat. Thus, most hydrogen fueled combined cycle plants would have an electrical yield near 42.5 %. This is about half of the efficiency of a pumped hydroelectric facility without the gas storage factored in, or about 38 % with H_2 storage factored into the process (with a 10 % energy loss due to storage of compressed H_2). Fuel cells are also cited as the potential generators for electrical storage systems. However, the fuel cell itself is only about 60 % efficient, and the rest of the energy stored in the H_2 is converted into low grade (and often unusable) heat. The overall efficiency for large stationary fuel cells then becomes 46 % before H_2 gas losses are factored in, and 41 % with the losses included. The fuel cell and the combined cycle facility are comparatively close in energy efficiencies.

If the fuel cell is used in transportation, the situation becomes even murkier. Hydrogen has a very high energy content per mole and per unit mass, but it is also the least dense gas in the periodic table, and has the second highest vapor pressure, next to helium. It is commonly transported as a cryogenic liquid for use in chemical synthesis, but up to 30 % of its potential energy is consumed in the condensation process. It can also be stored as a metallic hydride, but then heat energy must be expended to remove the H_2 from the complexed/adsorbed form. For small transportation units such as automobiles, high pressure H_2 gas storage is contemplated (at near 5000 psig, or 340 atmospheres), with associated compressor/compression energy losses. The overall efficiency of energy delivered to the electric motors of this transportation device would be near 39 %. When transportation of the H_2 from generation source to consuming point is considered, the overall efficiency drops to near 35 %. This efficiency would be less than using the electrical energy to charge batteries for an electrical car or truck, a viable option for most urban and sub-urban transportation tasks. Most batteries would have efficiencies of near 55 %, and these systems would avoid the complications of converting electricity to hydrogen, delivering and storing this fuel, followed by conversion of the fuel into electricity.

There are some significant problems that must be overcome if hydrogen is to become a new substitute for natural gas, as well as gasoline and diesel oil. Firstly, there is the matter of distribution, as hydrogen cannot be safely piped through the same pipelines as are currently being employed for natural gas. This is due to a phenomenon known as hydrogen embrittlement, which would render malleable steel pipelines as brittle as cast iron, and useless. The embrittlement effect is particularly accelerated at weld points in steel. In effect, all new high pressure pipelines would need to be installed. On a volumetric basis, natural gas has 3.64 times the energy per unit volume, so pipelines transmitting the same energy rate would need to be 1.9 times larger in diameter or operate at 3.64 times the pressure of comparable natural gas lines. Secondly, for transportation uses, there presently exists no significant transportation demand for H_2 – there are no meaningful quantities fuel cell cars in existence, so there is no demand for H_2, especially at a retail level. Finally, the "cleanliness" of H_2 is only as good as the energy source used to produce the H_2; without a large scale wind turbine base, significant H_2 production is unlikely to occur unless polluting energy sources (coal, oil, natural gas and nuclear) are employed. The storage of hydrogen for transportation is very energy intensive, requiring either cryogenic pressure tanks, or ultra-high pressure rated gas cylinders. Even at 340 atmospheres of pressure, a cylinder containing H_2 still has only 17 % of the usable energy that a similar volume of ethanol stored at atmospheric pressure possesses. A tank containing such high pressure also adds weight to a car, further lowering its performance. Lastly, fuel cells are forever likely to be capital intensive, requiring the use of noble metal catalysts such as platinum to be effective. In addition, there is the issue of the operating temperature range of automotive fuel cells to consider. In general, these systems are still experimental curiosities, and far too expensive to remain competitive with internal combustion engines. Many critics have noted how the hydrogen powered car can be used as a diversion from the installation of renewable energy production systems, since money spent on fuel cells has been obtained at the expense of energy efficiency and renewable energy research programs.

In contrast to the hydrogen situation, fuel ethanol is presently manufactured on a reasonably large scale (2.8 billion gallons in 2003), and most internal combustion engines can be converted to run on this high octane (with a 110 value) fuel with minor modifications. Ethanol is also easy to store and transport, relative to hydrogen, and has a considerably higher energy density (chemical energy per unit volume) than does hydrogen. There presently are over one hundred million operating internal combustion engines in the U.S., as well as a vast distribution network for gasoline which could just as easily dispense alcohol fuels. Ethanol can also be used in gas turbine applications, as a substitute for oil and kerosene. Thus, there is a huge "institutional momentum" that favors the use of ethanol, while there is the need for a huge capital investment of more than \$ 2 trillion (100 million cars at \$20,000 each) needed just for replacement of existing internal combustion based cars. In order to replace the existing stock of pollution-producing electrical generators (oil, gas, coal and nuclear), at least \$ 1 trillion would be needed. These huge capital requirements might necessitate a choice between the replacement of the present production techniques for electricity or the fuel source for automobiles and trucks.

CONCLUSIONS

The Great Lakes could become the electrical power source for the entire Great Lakes region using offshore wind turbines that could be installed in huge "mega-arrays". The electricity provided could replace all nuclear plants located along the Great Lakes, as well as all fossil fueled plants that do not co-generate (i.e. also employed for heating purposes). The average delivered power capacity of the combined U.S. and Canadian portions of the lakes is between 151 and 249 GW, or between 30 to 50 % of the 2003 combined U.S. and Canadian national electrical demand. The eventual power potential will be obviously a function of the lake depth that the turbines can be installed in, and the allowable portion of the lakes in which these farms would be allowed to be placed.

The aggregate average power production rate for the lakes is 3 MW per km^2 of lake surface, which varies by 1.368 MW/km^2, depending upon which lake is being evaluated. The order of per unit power potential appears to be Huron, Superior, Erie, Ontario, Michigan and St. Clair. The eastern shores tend to have the greatest potential, due to the direction of the prevailing winds. Initial offshore installations may be focused on the shallow, eastern shorelines located near urban areas and/or high power electrical lines, since those wind turbine arrays would have the lowest costs and quickest return on investments.

The most efficient means of temporary power storage seems to be pumped hydroelectric schemes. These can utilize a small portion of the vast water resources of the lakes in a recycling manner that would minimize potential pollution. There are several regions where elevated regions exist close to the lakes, and which are also reasonably close to populated centers (200 to 400 miles). At the present time, this power storage mode is approximately twice as efficient as hydrogen generation/fuel cell systems.

Given the current widespread usage of internal combustion engines, delivering portable energy in the form of ethanol is relatively easy. Ethanol and/or similar alcohols, or mixtures of methanol, ethanol and butanols could be a convenient means of delivering hydrogen to existing customers. The hydrogen could be provided both by the "natural" route of photosynthesis followed by fermentation and also by the reduction of carbon dioxide that is generated by microbial action (crop fermentation and also waste water treatment). If the hydrogen is supplied by renewable means for the carbon dioxide reduction, there would be negligible greenhouse gas contribution to the atmosphere, while a reliable and very usable liquid energy source is provided. For the time being, ethanol provided by carbon dioxide reduction using "green hydrogen" may actually be "greener" than the ethanol provided by crop fermentation.

The ethanol or other bio-fuels provided by crop fermentation can be made "more green" by incorporating larger amounts of wind turbine produced electricity into the entire production process of these materials. The steps towards this "greening" include production of the ammonia derived fertilizers (urea, ammonia, ammonium salts, nitrate salts) with ammonia synthesized from hydrogen produced by electrolysis using wind turbine generated electricity, nitrogen purified using wind produced electricity, and the use of the oxygen byproduct from the electrolysis operation. The actual fermentation and distillation steps are also energy intensive, and many of these could be accomplished with wind turbine produced electricity. The distillation of the ethanol from a 10 % ethanol/90 % aqueous solution can be accomplished very economically using electricity if the heat pump approach is employed.

The production of biomass fuels are ideally suited to the Great Lakes regions, where the combination of plentiful process water supplies, a population of nearly 38 million people in an area with a large industrial capability, and a large expanse of shallow lake area all are combined. Any excess electricity that is not directly used in traditional ways (lighting, motors, electronics, storage, etc) could be employed to produce hydrogen, which could be used to produce ammonia and/or liquid bio-fuels partly derived from crops grown with the ammonia based fertilizers. The liquid fuels could be employed as substitutes for gasoline in transportation systems, as well as substituting for kerosene and oil in applications such as heating, shipping, peak power production and gas turbine driven trains. In this manner, the people living near the Great Lakes could become largely energy independent from non-renewable fuels (coal, oil, natural gas, nuclear) for their electricity and personal transportation requirements.

Given the present pricing for natural gas and oil, wind turbine produced electricity is now less expensive than the fuel cost of natural gas and oil in combined cycle electrical generation units. The equal cost point for these differing electricity production methods occurred when the price of delivered natural gas reached $4.80/MBtu for land based turbines and $ 5.30/MBtu for offshore based turbines (the gas delivery cost is about $1.30/MBtu). If the natural gas price were to increase at a 3 % yearly rate from its present delivered price of \$7.50/MBtu, then wind turbines and water electrolysis would be a cheaper source of hydrogen than would the methane in natural gas in approximately 13 years. On the other hand, if gas costs rise by 8 % per year, the equivalence point will be reached in approximately 5 years. In either case, it seems more likely that any wind turbine derived electricity will be employed in established consumption patterns for the next few years.

The production of hydrogen must obviously go together with the consumption of hydrogen, and before a huge consumption of hydrogen occurs, a production system must be constructed. This can consist either of large electrolysis complexes, where the oxygen byproduct can be used or collected and sold, or small units where the oxygen is discarded, or combinations of both. Facilities that can get credit for the O_2 byproduct will be able to produce H_2 at lower costs – up to 9 % lower - than those facilities where the byproduct oxygen is discarded. Obviously, facilities with integrated hydrogen and oxygen production coupled to utilization of these materials would be more efficient than arrangements where extensive transportation of these products is required.

The elimination of fossil fuel based electricity production would result in less air pollution (acid rain, smog, heavy metals) and less strain on the water quality of the lakes. The elimination of nuclear power plants from the region would eliminate the potential for a Chernobyl-type accident, and resulting poisoning of significant portions of the lakes and associated watershed. And while the use of bio-fuels in automobiles and trucks may have a minor positive impact in the improvement of air quality, it would have several positive economic benefits, since the export of money outside of the region to pay for imported petroleum and natural gas would be lessened, and recycled regionally. One of the apparent prerequisites for large scale bio-fuels usage would be a higher price for natural gas and oil. This higher price should also act as a discouragement to additional automobile fuel usage (via greater fuel efficiency and/or less driving), and thus lessen the "smog load" due to consumption of any combustible liquid fuels.

Finally, large numbers of wind turbines placed on the shallow regions of the Great Lakes would have regional effects. Monetarily speaking, this would be a tremendous boost to regional economic activity, providing spin-offs such as in construction, shipping and possibly steel industries. Ecologically, a large percentage of the country's carbon dioxide pollution could be eliminated, with the added benefit of lowering the "greenhouse stress" on the planetary atmosphere and ecosystem. The wind turbine towers would serve as fish breeding sites, much like reefs or piers function. This may be either a positive or negative feature, depending upon a complex interaction of the local ecology, which has been severely altered over the last 200 years. If large scale electrolysis facilities are located near Lake Erie, there is the possibility of using some of this oxygen byproduct to remedy the "dead zone" in the deep part of this lake. For example, if the deep region of Lake Erie is assumed to be approximately 50 km x 20 km x 20 meters deep, a volume of 20 km^3 of water would need to be oxygenated to near an O_2 content of 5 ppm. This process would require 100,000 tonnes of O_2 per year, and would be the byproduct from the production of 25 million lbs per year of hydrogen, or that produced by a 60 MW electrolysis facility. Such is the price of repairing the damage to Lake Erie from years human induced stresses, including zebra muscles, fertilizer runoff, sewage runoff and the accumulation to too much biological material in the deep zone of this body of water. However, the O_2 injections would need to be properly researched before it is attempted, as this could be a very complicated situation from an ecological vantage.

RECOMMENDATIONS

The large scale production of wind generated electricity could have several positive benefits to the region, but there may also be drawbacks related to real ecological problems, as contrasted with the view of a few. One of these concerns is the possible recontamination of the lake waters when sediment is disturbed during the installation of the towers. Another would be the effect of placing large numbers of turbine tower foundations across the lakes on the aquatic ecology. For example, if large numbers of fish take up residence near the towers, the question arises as to what kinds of fish, and how would this affect the food web of each lake. If large numbers of fish begin living next to the towers, would that also attract large numbers of birds? If so, which ones? Would the birds attracted to the fish become endangered by the turbines, or the birds preying on the large number of foraging birds attracted to the fish around the towers. Would these additional breeding sites for zebra muscles cause any more problems?

There are also other unknowns, such as the real, as opposed to roughly estimated, average wind speeds across the Great Lakes. What are the roughness lengths of the lake surfaces when the lakes were not covered with ice? What would be the best strategy to deal with the occasional ice that forms with diminishing frequency on the lakes?

These and many other unknowns should be investigated prior to such a massive undertaking as tapping the Great Lakes for great amounts of energy. One way to do this would be similar to the recent Danish offshore program. Both the Horns Rev and Nysted wind farms were conceived as pilot projects. Not only are the operations, economics and construction methods being extensively monitored, but the avian and aquatic environments are being extensively studied (for example, see http://www.hornsrev.dk). One fine possibility for a demonstration project would be the Buffalo Harbor, where an offshore wind turbine array could be located next to a major urban center, complete with local universities and several existing research and regulatory agencies, such as the Army Corps of Engineering, the NYDEC, Buffalo State College and SUNYAB.

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References

1. http://www.glerl.noaa.gov/data/char/bathymetry.html (bathymetric data)

2. Wind Turbine Performance: http://www.windpower.org
   and http://www.windpower.org/en/tour/wres/pow/index.htm
   and http://www.windpower.org/en/tour/econ/econ.htm

3. NH_3 : Haliburton Corp KAAP process

4. Hydrogen: Production and Marketing Smith & Santengelo
   ACS Symposium Series, # 116 American Chemical Society, 1980

5. Tomorrow's Energy – Hydrogen, Fuel Cells and the Prospects for a Cleaner Planet Peter Hoffmann, MIT Press (2001)

5. Horns Rev Project website: http://www.hornsrev.dk

6. Nysted Project website: http://uk.nystedhavmoellepark.dk/frames.asp

7. Nysted/Rodsand wind resource study:
   "Description of the Rodsand Field Measurement", Riso-R-1268(EN)
   by Lange, Barthhelmie, Hojstrup, Riso National Laboratory, Denmark,
   May, 2001, file = ris-r-1268.pdf, ISBN 87-550-2885-3 (Internet)

8. "Wind Energy Explained – Theory, Design and Application",
   Manwell, McGowan, Rogers, Wiley, (2002)

9. Ethyl Acetate Process Technology: Davy Process Technology brochure
   File = 8.115-Ethyl Acetate.pdf

10. Wind Energy, 2003; 6:405-412, Skegness, Great Britain wind data

11. "Wind Eenergy Statistics for Large Arrays of Wind Turbines (Great Lakes
    and Pacific Coast Regions), C.G. Justus, W.R Hargraves
    Annual Progress Report, April 30, 1977, RL/2439-77/2
    U.S. Department of Energy, contract # EY-76-S-06-2439

Appendix A

Estimation of Offshore Array Efficiency – 6.25 x 6.25 Rotor Diameters

The owners of the Horns Rev wind farm, which is located off the southwestern coast of Denmark, have stated that the expected output of the turbine array is 600,000 MW-hr per year. Since there are 80 turbines installed on an offshore reef, the expected turbine output would be 7500 MW-hr per turbine. This value would take into account maintenance, repairs and especially the array inefficiencies that occur when upwind turbines impede the air flow towards the downstream turbines. These turbines are placed on towers such that the hub height of the turbine averages 70 meters above the water (the tidal range is about 4 meters at Horns Rev). These turbines have 80 meter rotor diameters and area spaced 500 meters apart in a rectangular pattern, or 6.25 rotor diameters. The question arises, what is the array efficiency?

The wind resource at this location was extensively monitored by a tall tower, multi-anemometer tower, and the wind speeds are reported on the website for the project, http://www.hornsrev.dk/Engelsk/default_ie.htm (→ Horns Rev → Wind Conditions) in a graphical form that includes the wind speed distribution. The average wind speed at 62 meters was 9.5 m/s, with a Weibull wind distribution k factor of 2.3 (this denotes that shape of the curve of wind speed plotted versus the probability of a speed occurring). The wind speed graph is shown below in Figure A1:

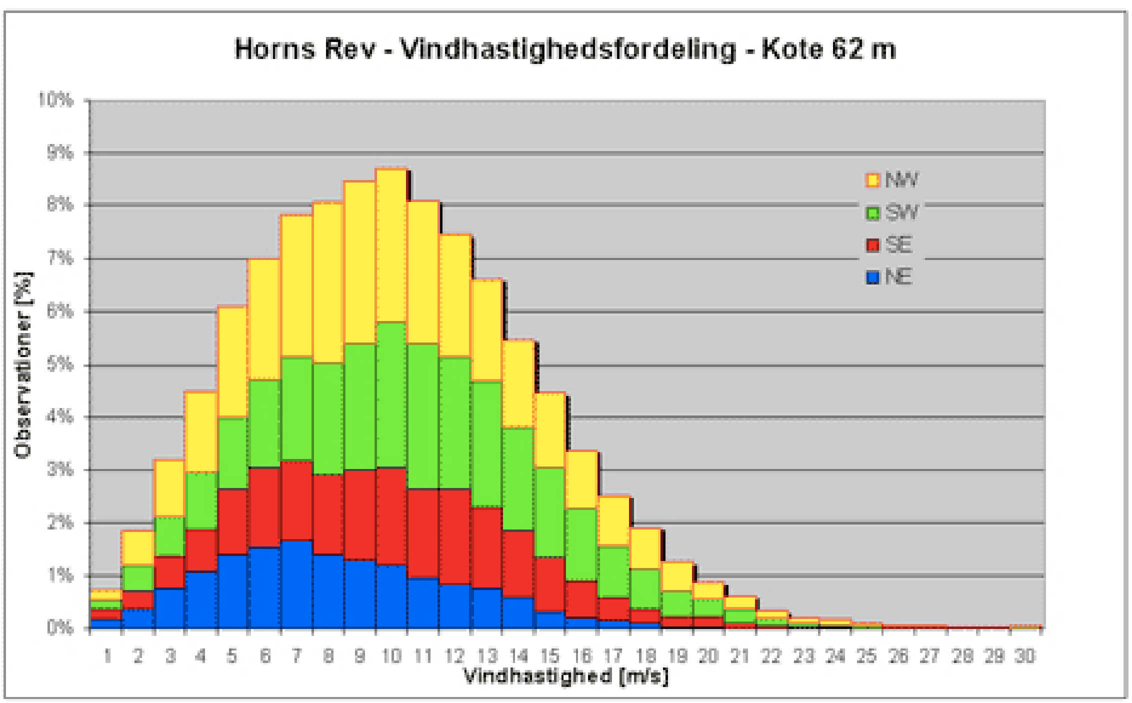


Figure A1
Horns Rev Wind Speed Distribution
Source: http://www.hornsrev.dk

This information can be used with the Wind Turbine Energy Calculator on the website http://www.windpower.org for the Vestas V80 wind turbine. The specific conditions are an altitude of 0 meters (sea level), 8 C average temperature, surface roughness of 0.005 meter and a hub height of 70 meters. Given a wind speed of 9.5 m/s and a Weibull shape factor of 2.3, the scale factor, which is the other required parameter for this probability function, is computed to be 10.7. The estimated wind turbine output should be 9518 MW-hr per year. Since the given output per turbine is 7500 MW-hr per year, the average array efficiency is 78.8%, or 7500 divided by 9512. Given the approximate nature of the 7500 MW estimate, the average efficiency can be approximated as 80 %. The comparison between the predicted curve and the actual data is shown in Figure A2.

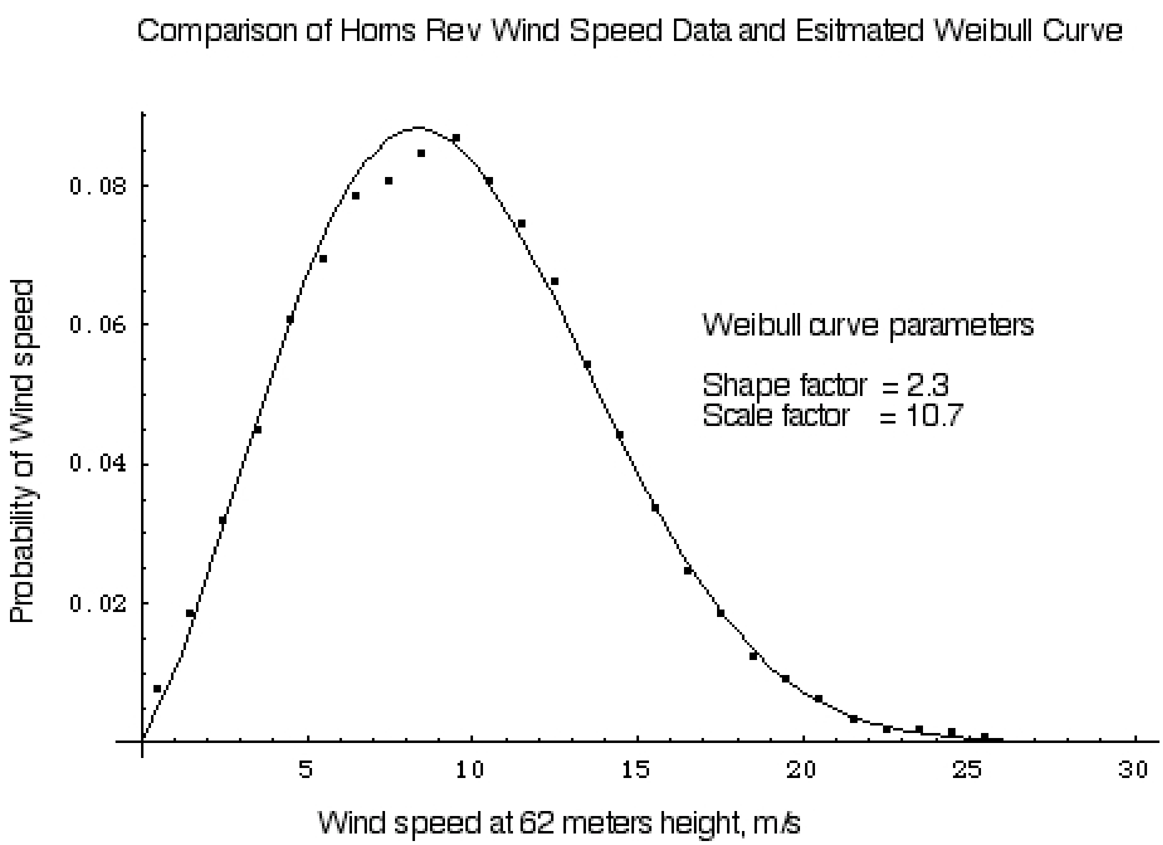


Figure A2
Weibull Wind Probability Curve for Horns Rev at 60 meters Height

Although this is admittedly a crude synopsis of several factors, including scheduled maintenance, repairs and shutdowns due to grid requirements, this serves as a basis for the 80 % array efficiency estimate. This may actually understate the actual power output; at the Middlegrunden wind farm, the energy output was 7 % greater than expected from wind measurements. The Middlegrunden wind farm is located in Copenhagen harbor, about 3 km from land.

Appendix A2

The Nysted wind farm is located in the Baltic Sea in eastern Denmark. It consists of 72 x 2.3 MW Bonus wind turbines with hub heights 69 meters above the water line, placed over a 22.8 km^2 area. Some of the wind speed data for this location have been published by Denmark's Riso National Laboratory in 2001; these are graphical depictions of the wind speed measurements obtained at a wind test tower. In particular, data are shown for the wind speed distributions at 10.2 meters and 50.3 meters heights, where the average wind speeds were 7.15 m/s and 8.92 m/s, respectively. The distributions indicate a very similar shape factor for the winds at Nysted and at Horns Rev of near 2.3, and the wind shear exponent and surface roughness factor can be calculated. The wind shear exponent for the 10.2 to 50.2 meter rage is 0.1384, while the roughness length is near 0.01610 meters, which is considerably more than the usual sea surface values of 0.001 to 0.005 meters. This may be due to the Nysted location, where several islands are situated nearby. Given these values, the wind speed at a hub height of 69 meters would average 9.27 m/s.

The power output of an individual Bonus 2.3 MW wind turbine with such a wind resource would be 10,140 MW-hr/yr. The estimated output of the Nysted array is given as 595 GW-hr/yr, or 8263 MW-hr per turbine per year. The array efficiency would be 81.5 % for this location.

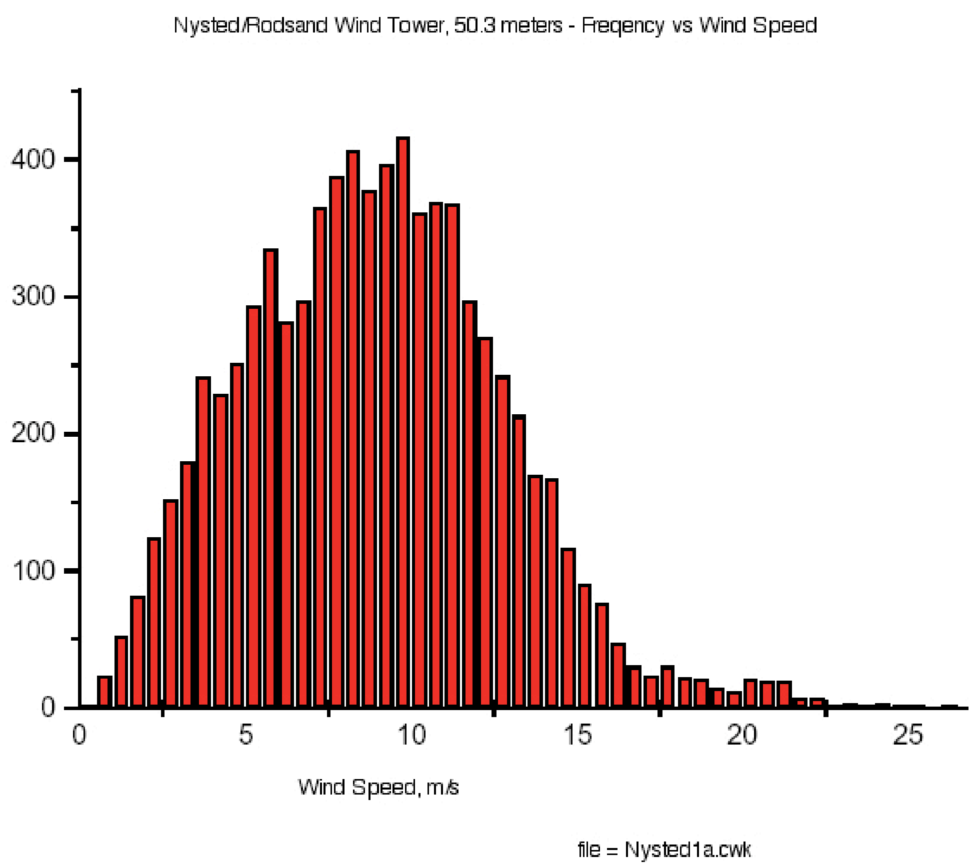


Figure A3
Nysted Wind Tower Data at 50.3 Meters Height

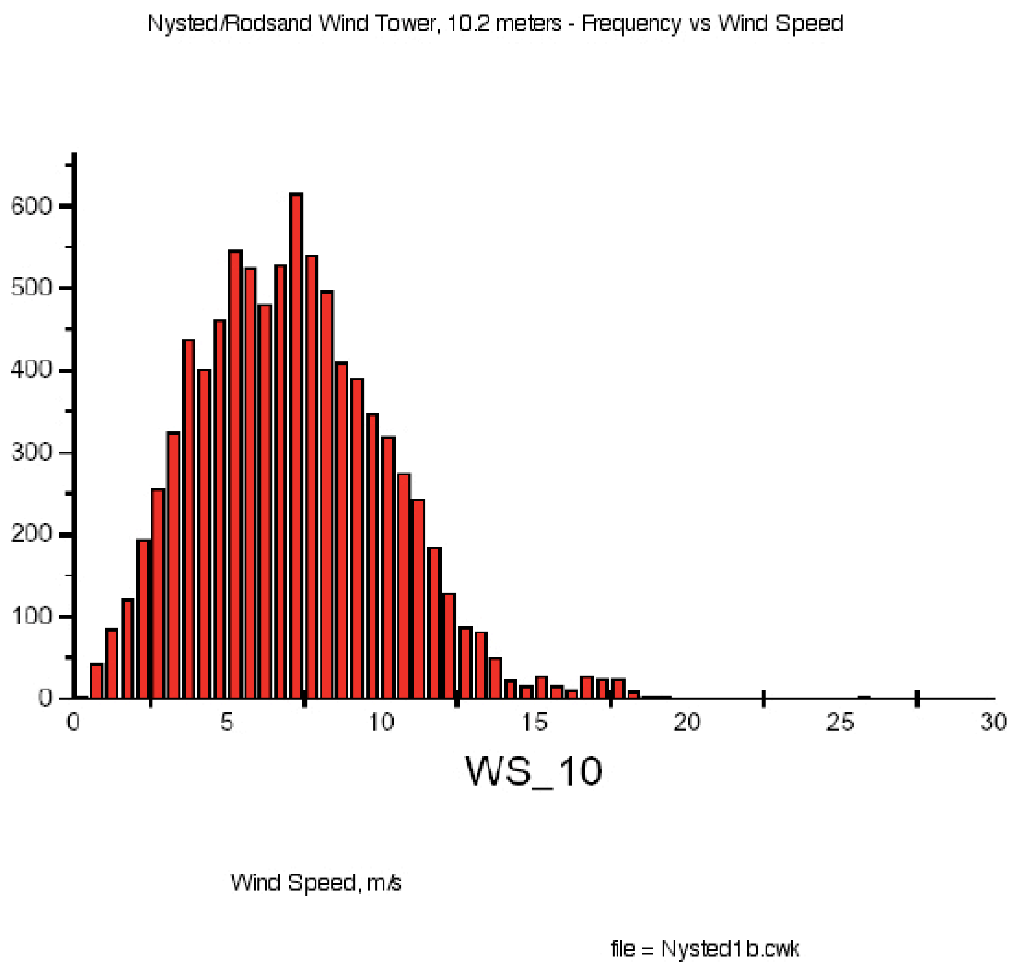


Figure A4
Nysted Wind Tower Data at 10.2 Meters Height

Appendix A3

Estimation of Roughness Lengths for Large Water Bodies

The theory behind roughness lengths, and how to estimate them on a theoretical basis can be extremely complex. However, the best estimates are invariably those that are derived from actual measurements, such as with the tall offshore towers at Horns Rev, Rodsand/Nysted and Skegness. The wind speeds at two different heights can be used to determine the roughness length using the following formula, which is derived from (1) on page 18:

$$z_0 = Exp\left[\frac{\ln\left({h_1}^R / h_2 \right)}{R - 1} \right] \quad \text{where} \quad R = \left(u_2 / u_1 \right)$$

In this form, z_0 is the roughness length while R is the ratio of the measured wind speeds u_2 (at height h_2) and u_1 (at height h_1). The values of z_0 are affected by the wind speed as well as the distance to land from which the wind has traveled, so that roughness values for parts of lakes or oceans far removed from land may be less than those for waters near land.

An empirical relationship between wind speed and roughness length values shown in Figure A5. The curve was obtained by a least fit squares approximation of the data given in the Journal of Physical Oceanography, November, 1979, pg 1243 to 1257. When this data is used for the Nysted sight, the wind speed at 10.2 meters (very close to 10 meters) of 7.152 m/s corresponds to a roughness length of 0.0193 meters. Using the logarithmic formula (1), the calculated wind speed at 50.3 meters of height is 8.963 m/s, while the measured wind speed from the data in A2 is 8.92 m/s. The calculated value is less than 0.5 % above the measured value, which is reasonably accurate.

In Table A1, the calculated roughness lengths for the Great Lakes are listed

Table A1
Great Lakes Roughness Lengths from Tsahalis Paper

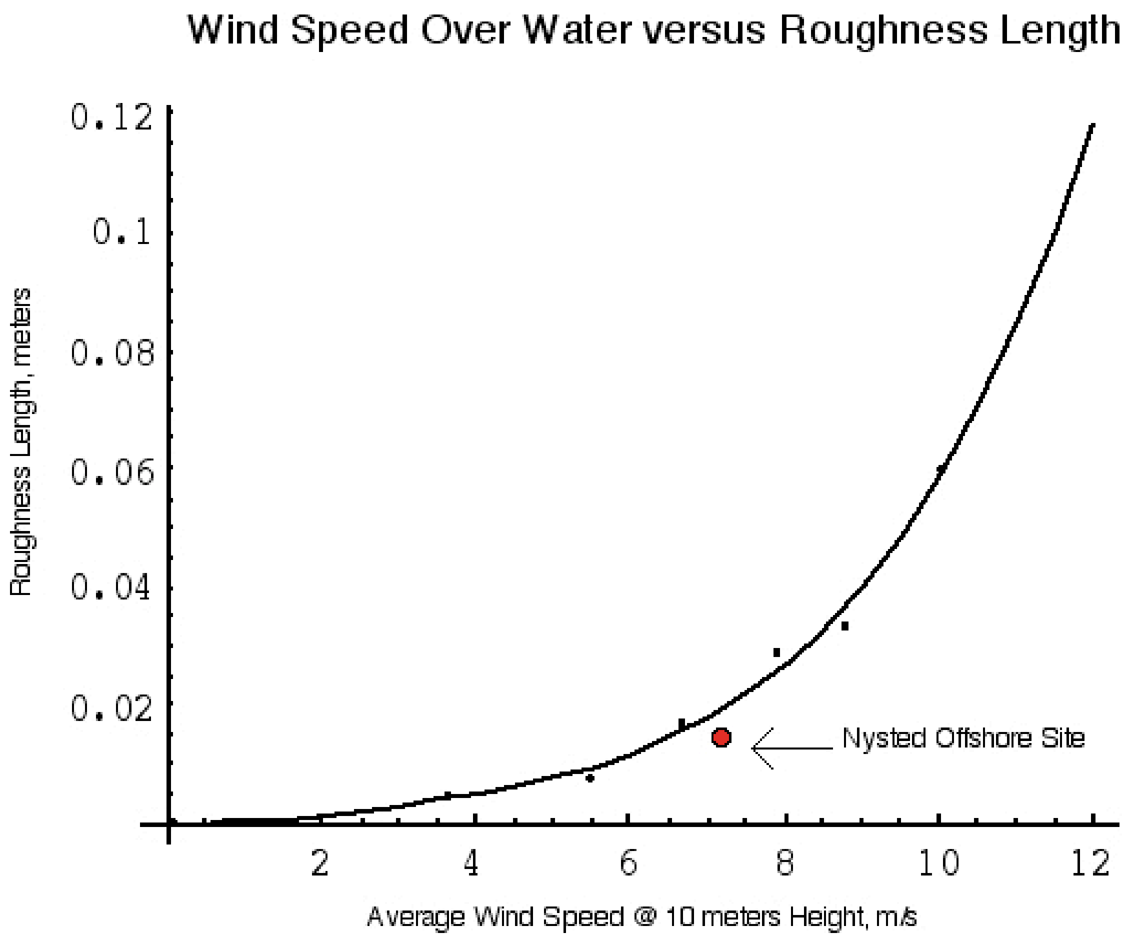
Lake	Av Wind Speed m/s	RL m	U est,70m m/s	U est, 90m m/s
Ontario	6.42	0.01465	8.33	8.58
Erie	6.56	0.01551	8.55	8.80
St. Clair (a)	5.5	0.01019	7.05	7.25
St. Clair (b)	5.0	0.00820	6.37	6.55
Huron	7.27	0.02023	9.55	9.84
Michigan	5.82	0.01160	7.50	7.71
Superior	6.63	0.01587	8.63	8.89

This can be compared to the more conservative values used in Table 3:

Table A2
Great Lakes Wind Speeds Where Roughness Lengths = 0.005 meter

Lake	Av Wind Speed m/s	RL m	U est,70m m/s	U est, 90m m/s
Ontario	6.42	0.005	8.06	8.28
Erie	6.56	0.005	8.25	8.47
St. Clair (a)	5.5	0.005	6.91	7.09
St. Clair (b)	5.0	0.005	6.28	6.45
Huron	7.27	0.005	9.13	9.37
Michigan	5.82	0.005	7.31	7.50
Superior	6.63	0.005	8.33	8.55

There is a 5.7 % gain for the Lake Erie estimate using calculated roughness length values instead of the 0.005 meter estimate from the Skegness location. The energy production values for an individual Bonus turbine are 8181 MW-hr/yr (RL = 0.005) and 8648 MW-hr/yr (RL = 0.01551). Using the more conservative roughness length numbers results in a more cautious estimate of the Great Lakes power potential. The situation is even more pronounced for Lake Huron, where the energy output values are 10,004 MW-hr/yr (RL = .02023 m) or 9423 MW-hr/yr (RL = 0.005 m), a 6.2 % difference.



Formula, where x is the average wind speed in m/s (curve fit, Table3, pg 1249 :

RL = Out[255]= $0.000519687\ x^2 - 0.0000871598\ x^3 + 9.34046 \times 10^{-6}\ x^4$

Source: D.T. Tsahalis, Journal of Physical Oceanography, November, 1979, pg 1243-1257

Figure A5
Empirical Roughness Length Calculation of Water Versus Wind Speed

Curve fit via Mathematica

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