NAVAL & Non-NAVAL WARP^{tm} OFFSHORE WIND POWER SYSTEMS WITH INTEGRAL FUEL CELLS

Alfred L. Weisbrich, P.E.
ENECO Texas LLC
West Simsbury, Connecticut, USA
e-mail: enecowind@aol.com

William Smith
Co-founder Proton Energy Systems
Proton Energy Systems
Rocky Hill, Connecticut, USA
e-mail: wsmith@protonenergy.com

Günther J. Weisbrich
ENECO TX
Dallas, Texas, USA
e-mail: enecotexas@aol.com

ABSTRACT

Environmentally clean and green energy is becoming increasingly a requirement of electric power delivery systems. The focus on energy security and terrorism makes an indigenous, sustainable and distributed energy resource increasingly attractive. Distributed wind power has been shown to be a good and economic means for generating clean power in good wind sites, even on an intermittent basis. However, the best wind sites are located offshore where deeper water makes current large bladed windmills uneconomic. A low cost and patently unique modular wind power technology, designated a Wind Amplified Rotor Platform (WARP^{tm}) system technology, has been investigated which projects attractive technical and economic benefits when tension leg deployed in deeper water sites where big rotor windmills are impractical. Under marine offshore use these designated e-Sea WARP^{tm} units may include integral gas turbines or fuel cells. The latter may co-generate with WARP windpower generated hydrogen fuel stored in onboard buoyancy tanks to supply on-demand electric energy which may be shown to be under \$.02/kWhr to under \$.04/kWhr. Electrical loads from electric utilities, military facilities or on-board naval operations may be serviced. Large environmental, economic, and strategic benefits may be realized by use of this technology for commercial and/or naval/ coast guard sentry operations. In essence, e-Sea WARP^{tm} systems may provide sustainable ultra-clean on-demand electricity to onboard naval systems or to nearby energy demand centers on shore by submarine cable from normally excellent wind sites miles from shore at sea.

INTRODUCTION

With concerns about environmental pollution, energy security and terrorism becoming more critical with time, the trend toward use of an indigenous clean, economically accessible and sustainable energy resource such as windpower is becoming increasingly attractive.

Consequently substantial effort has gone into research and development of wind energy systems and search and selection of locations where relatively high mean wind speed exists. The reason for the latter is clear. As wind speed increases, collectable energy from the wind increases by the third power. That is, in a location with a 20% higher mean wind speed than another, it is possible to produce over 70% more power. If a 50% higher wind velocity is available, well over 300% more power and energy can be generated.

It has been determined that excellent and widespread high wind energy exists on large bodies of water, even relatively close to shore where large energy demand centers also typically exist, including cities and naval installations.

But studies in the US and Europe have found that large diameter windmills in offshore installations are relatively uneconomic, other than in very shallow sites, due to a number of their unavoidable characteristic features as discussed later.

However, an advanced concept modular wind amplifier technology, designated a Wind Amplified Rotor Platform (WARP^{tm}) system (see Fig. 1a & b), has been designed and researched which projects extraordinary technical and economic advantages and benefits over current big bladed windmill designs, including adaptation for deep water site installation.

Fig. 1a WARP Tower & Yaw Flow Amplifier Module

Fig. 1b Passive Yaw WARP Flow Amplifier Module

WARP technology avoids virtually all the nagging problems faced by current large bladed windmills. The latter include large blade and large gearbox failures, large area sprawl requirement due to inter-unit interference, visual detraction and strobe effect, noise, telecommunication interference, bird kill, and high susceptibility to lightning damage. For reasons of good wind, large land use, safety risk and detrimental visual impact, the wind industry, particularly in Europe, is venturing into the wind rich offshore marine environment. However, despite the potential of thereby solving some of the stated problems, the limitation of large rotor windmills to shallow water sites and their costly foundation and maintenance issues are preventing the full potential of offshore windpower from being realized. E-Sea WARP systems, as will be described, can avoid virtually all the stated problems of today's windmills and are also projected to have easier deployability and maintainability at lower cost as well.

Nevertheless, the WARP design benefits from conventional windmill research and development related to blade aerodynamics, blade structure, electric power conversion and controls for horizontal axis (propeller)-type wind turbines, including for offshore application. Windmill R&D has to date dealt primarily with the inherent risks and unknowns of large rotorhead windmills due to a history of past blade and gear failures. Failures have included the first large diameter windmill, the 1.2 MW Putnam turbine built in the 1940's on Grandpa's Knob, VT, USA. Current era utility scale wind turbines built by the US aerospace industry and windpower industry have had similar events. In contrast, WARPs require no large rotors and gearing, thereby circumventing these key issues..

WARP^{tm} /e-Sea WARP^{tm} DESCRIPTION

The basic Wind Amplified Rotor Platform (WARP^{tm}) windpower system design consists of stacked wind amplifier modules with an integrated multiplicity of small diameter, simple, yet high capacity gearless wind turbines. Its basic features have been described in various feature articles of key publications, samples of which are provided in the noted references [1-5].

As illustrated in Fig. 1a, b, c & d, alternating static and yawable toroidal wind amplifier modules are peripherally mounted to a simple core tower. These modules, which can vary in size relative to each other, create at each elevation level an omnidirectional peripheral flow channel. Therein, about 180 degrees apart, a pair of small diameter, high capacity, wind turbines are attached. These may require no step-up gearbox. Such turbines are expected comparable in size and reliability to aircraft propellers (2 meters (m) to 3 m diameter) which have hundreds of millions of passenger miles of successful operational history. WARP systems can be easily customized to virtually any power capacity. By virtue of its modular amplifier building blocks (also referred to as TARPs) height limitations of large bladed conventional windmills are eliminated. This opens the prospect for constructing single large units with capacity up to 50 MW. Units of this scale would be comparable in height to existing tall buildings or high definition TV (HDTV) towers. Such super-capacity WARP windpower units would generally, however, be expected to incorporate rotors larger than 3 meters and have functions beyond simply energy generation.

Stacked WARP modules can amplify the ambient wind speed on average over 150% to 180% to the incorporated wind turbines (see Fig. 1 c). Together with associated flow tailoring by the amplifier flow channel, this provides a means for greatly superior wind turbine performance compared to free air operation. Furthermore, the aerodynamic toroidal module structure has multi-tasking use which can improve economics substantially (see Fig. 2).

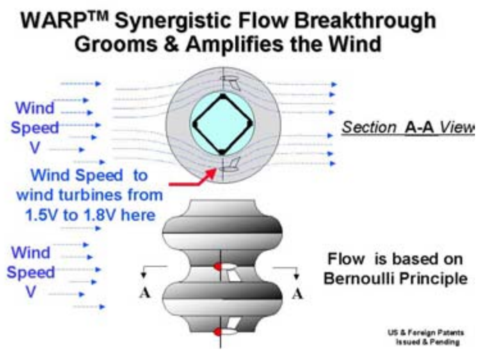


Fig. 1c WARP Module Flow Amplification to Turbines is based on Bernoulli Principle

Specifically, WARP wind amplifiers increase wind energy density and provide structural benefits such as securing the turbines, passively yawing the turbines into the wind, and strengthening the core tower via ring stiffening by each static module which complements each yawing module. Fortuitously, typical size WARP wind turbine optimum rotor RPM tends to closely match available stock generator speeds, if constant speed induction machines, eliminating the need for gearboxes.

Another extraordinary feature is that WARP turbine generators can be internalized to the modules. This can avoid transmission of rotor thrust loads to the generator and allow optimizing rotor-to-generator speed matching. Plus it provides ready internal access to the relatively manageable size generators, typically in the 10 kW to 50 kW range, for ease of servicing. See Fig. 1d.

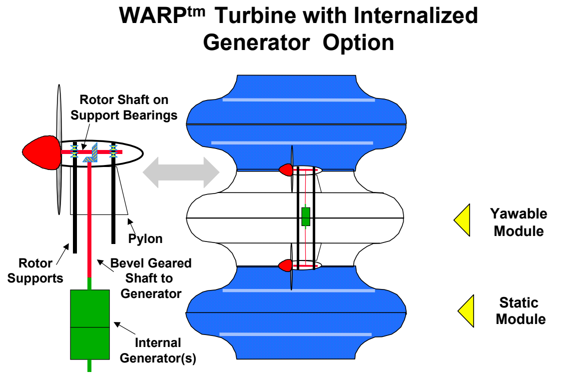


Fig. 1d Internal WARP Generators Can Provide Added Optimization, Access & Cost Benefits

Analyses, Wind Tunnel & Field Tests

Analysis and model and free air testing has been conducted on WARP to date in conjunction with Rensselaer Polytechnic Institute (RPI) and the New York State Energy Research & Development Authority (NYSERDA), and other organizations such as the Technical University of Graz, Austria, Raytheon, the Danish Maritime Institute (DMI) commissioned by LM/NEG-Micon, and others. The technology has undergone convincing analytical assessment, including computational fluid dynamics (CFD), wind tunnel testing and development of a pre-prototype field test unit. Initial wind tunnel tests of isolated single (not stacked) WARP modules at RPI resulted in wind amplification of over 20% to 50% over ambient wind speed to turbines (i.e.; 1.2 and 1.5 Velocity Amplification Factor (VAF) over free wind). Due to the cubic effect of wind on a wind turbine, the latter translated into more than 3 times the power over a wind turbine in the free air. This, in connection with a breakthrough synergistic flow effect which maintained flow attachment about the WARP flow channel to over 140 to 160 deg. from head on, validated and encouraged pursuit of the concept. Initiation of subsequent licensing discussions in Europe led to commissioned CFD investigations at the Technical University of Graz, Austria. These investigations in 1996 revealed that tall stacked arrays of WARP modules could produce VAF of 1.7 to 1.8 on average. The foregoing is documented in cited references [6-11] The latter WARP performance thus projected to exceed that of results reported in papers dated 1996 or earlier, such as IEEE Transaction Journal and American Power Conference technical papers [6-10], some of which formed the basis of Raytheon's proposal of WARP to the NREL / US Department of Energy.

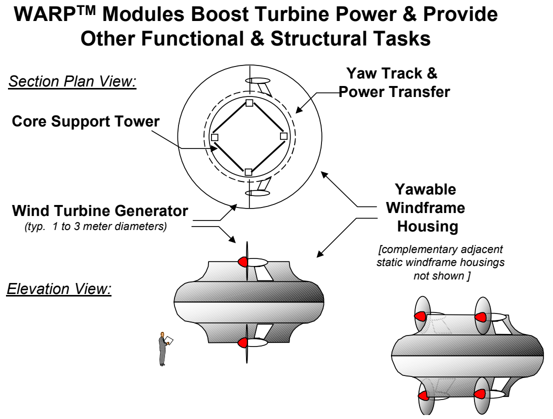
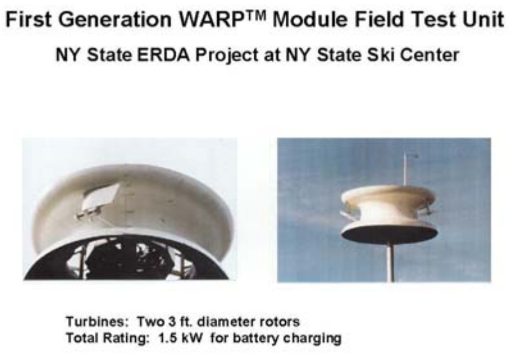


Fig. 2 WARP Modules Can Amplify Free Wind 80% & Have Multi-Tasking Features & Benefits

A single first generation WARP pre-prototype module was subsequently built at the highest point in the New York State Catskill region of Ulster and Delaware counties with support from the New York State ERDA (NYSERDA).



First Generation WARP™ Module Field Test Unit

NY State ERDA Project at NY State Ski Center

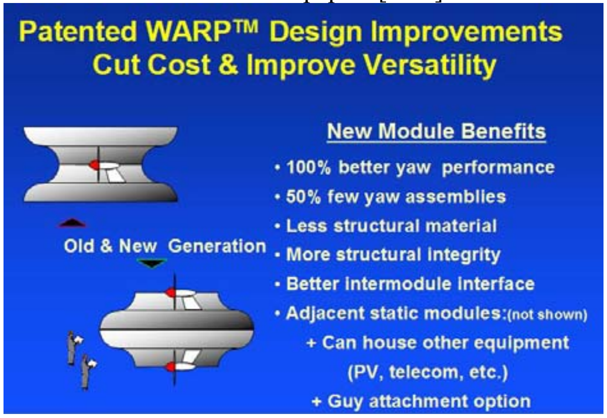
Turbines: Two 3 ft. diameter rotors
Total Rating: 1.5 kW for battery charging

Figure 3. First Generation Test Module with Turbines Replicated Wind Tunnel Flow Characteristics

The test installation consisted of twin 3-foot diameter wind turbines, 1.5 kilowatt in total capacity, mounted to the isolated single module on a commercial 60-foot tall tubular tower. Video and photo-documented flow visualization of the unit verified that the flow field behaved virtually identically to that of the same module configuration tested in the RPI wind tunnel.

However, due to siting restrictions, the unit tower had to be closely positioned near the edge of a 45 degree sloped cliff that faced the prevailing northwest winds. Hence, the prevailing winds impacted the module flow channel at a roughly 45 degree upwash angle. As a result, the flow amplification in the channel and performance of the wind turbines therein were compromised under these upwash flow conditions. Furthermore, in January of 1996 a disastrous force majeur wind storm occurred near the end of the project while waiting for proper level flow wind conditions from the northeast direction for useful performance data gathering. The impact of this 100-year storm caused the two county Catskill region of Ulster and Delaware, New York to be officially declared a disaster area. The WARP module, located at the highest point of this area, experienced about 140 mph winds but survived intact, despite fatigue failure of a metal support arm extending between the module and the tubular tower. All customized test instrumentation on the module was, however, destroyed preventing further test operations. With project funding exhausted, the project was terminated and the unit subsequently dismantled. Nevertheless, with the module having survived this 100-year wind storm, it demonstrated the structural resiliency and inherent strength of the toroid module configuration which was made of only one eighth (1/8) inch thick spray-up fiberglass skin panels supported internally by a steel frame at 3 points about the module periphery. In a prior but less severe storm, the unit also successfully demonstrated fail-safe module yaw parking (i.e.; system shut down) when a flaw in a vendor's rotor hub caused it to throw a rotor.

Subsequent to termination of this test program, ENECO embarked on major cost reducing and performance enhancing design improvements. These resulted in patented improvements also in structural strength, and application versatility. (See Figure 4). Energy cost is projected to be significantly reduced relative to that reported in prior IEEE Transaction Journal and American Power Conference technical papers [6-10].



Patented WARP™ Design Improvements Cut Cost & Improve Versatility

Old & New Generation

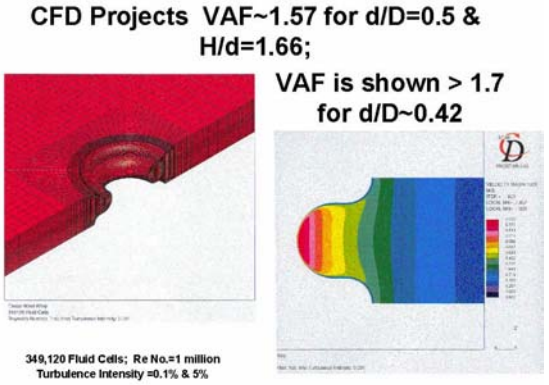
New Module Benefits

- 100% better yaw performance
- 50% few yaw assemblies
- Less structural material
- More structural integrity
- Better intermodule interface
- Adjacent static modules:(not shown)
  - + Can house other equipment (PV, telecom, etc.)
  - + Guy attachment option

Figure 4. WARP Design Improvements Cut Cost & Enhance Performance Further

Performance

Based on wind tunnel tests and independent CFD studies, the WARP modules are shown to accelerate the ambient wind to well over 50% to 80% on average (i.e.; Velocity Amplification Factor (VAF)=1.5 to1.8) over the rotor disc area, depending on configuration and stacking aspect ratio [11]. (See Fig. 5).



CFD Projects VAF~1.57 for d/D=0.5 & H/d=1.66;

VAF is shown > 1.7 for d/D~0.42

349,120 Fluid Cells; Re No.=1 million
Turbulence Intensity =0.1% & 5%

Figure 5. CFD Analyses Show WARP Modules Can Amplify Wind Speed over 1.7 Times Free Wind

For example, *a 65% increase in wind speed can yield 450% more power and energy due to the cubic effect of wind speed on power*. This output is enhanced by WARP system height, which can access the higher winds aloft due to wind shear. The gearless direct drive and partial tip shrouded turbines eliminate and reduce gearing and tip losses, respectively. WARP capture area can therefore be less than for comparable power conventional windmills, which translates to higher system efficiencies. Rated capacities of utility scale WARP wind turbines are projected between 5kW to 50 kW each, depending on site mean wind speed and module configuration and rotor diameter (d). Up to 25% performance loss due to bug & rain impact on exposed large turbine blades is also avoidable by WARP rotors.

WARP power capacities to tens of megawatt levels can be readily assembled and site tailored. A major benefit with the WARP module building block design approach is that expensive rotor re-design and re-tooling is eliminated when new capacity system*s* are desired. Instead, multiple WARP modules, each having common rotors, common stock generators of specified capacity, can be stack-arrayed on a common tower to achieve desired system power capacity.

Figure 6 illustrates parametric curves of power output capacity for WARP systems having various number of rotor levels in designated mean wind speed sites when each wind turbine rotor diameter is 3 m (~10 ft) and the VAF is 1.7 in the specified module configuration.

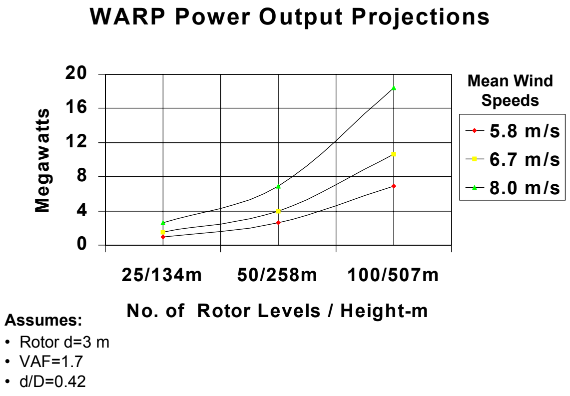


Fig. 6 WARP Power Capacity Can Be Easily Customized with Module Number

WARP Mass Production & Capacity Customization

WARPs' simple and relatively small sub-components are well suited for low cost volume production, ease of transportation, erection and servicing. Therefore, WARP system cost and costs of energy can be attractively low and competitive [12-14].

Mass production has long been recognized as an effective means of reducing a product's unit cost [15]. It has enabled manufacturing companies around the world to produce high-quality products that leverage the economies of scope based on division of labor and automated, standardized components and processes. Everything from complex systems like automobiles and personal computers to the simple plastic deck stacking chair are example of this significant cost reduction through volume production. The principle drivers are the learning curve and the bulk purchasing power afforded by large quantity of identical components.

The modular WARP systems design is ideally suited to provide standardized sub-components and modular repetitive sub-assemblies for mass production and procurement benefits (see Fig. 7). Capturing the efficiencies of mass customized WARP wind power plant design is an approach that has been promulgated by ENECO in its R&D in connection with Rensselaer Polytechnic Institute and the New York State Energy Research & Development Authority (NYSERDA). Noteworthy is that one or two uniquely shaped panels can form the basis for the entire exterior aerodynamic skin structure of a WARP system. This, along with repetitive tower and turbine sub-assemblies, lends itself to cost effective system mass production.

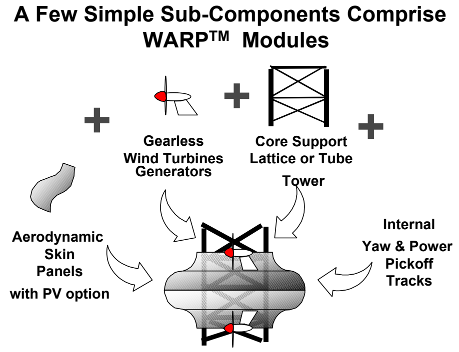


Figure 7. WARP is Readily Volume Produced for Low Cost

WARP Environmental Benefits

WARP environmental benefits are large compared to traditional fossil-fired power plants. However, WARPs also have improved features relative to conventional large diameter rotor windmills. Despite their non-air polluting energy generation, today's big bladed windmills have nagging environmental problems, structural risks and liabilities. These include large unsightly land/area sprawl, bird kill, far field noise, blade failure, effluent from hydraulics or gearbox transmissions, susceptibility to damage or destruction from lightning, and telecommunication/TV interference due to the need for metallization on their large blades for lightning protection purpose. WARP systems virtually avoid all these problems. These resolutions are presented in more detail in reference [16].

WARPS & PV, GAS TURBINES OR FUEL CELLS

WARPs are suited to internally co-locate and co-generate with other power systems. These can include solar cells, gas turbines and fuel cells. For example, a WARP system may uniquely and economically add ~5% to 10% more electric power capacity by integrating photovoltaic solar cells (PV) to its common WARP skin or internal structure. Since 50% of the cost of conventional stand-alone PV systems typically resides in PV module structural support (only 25% is cell cost) [17], "piggybacking" solar cells on WARP amplifier modules embedded on its aerodynamic structure skin panels can make PV much more cost effective. Complementing wind and solar energy can thus be captured and converted.

However, in order to achieve an ultra-clean, on-demand power output capability, WARP systems are proposed to co-operate with either gas turbines or Proton Exchange Membrane (PEM) fuel cells co-located within its internal tower housing. The preferred approach is to operate either the gas turbines or fuel cells on hydrogen fuel generated by excess WARP wind power. When the wind turbines are operating below demand capacity, gas turbines or fuel cells may rapidly come on line to pick up the required balance of load demand. If located offshore and used for naval/coast guard operations, units can draw on stored energy for onboard facilities &/or weaponry.

NAVAL & NON-NAVAL OFFSHORE WARP SYSTEMS APPLICATIONS

Modular WARP systems lend themselves for adaptation to floatation and have been investigated for integration to offshore navigational buoys and oil platforms [18]. This subsequently prompted a conceptual scale up of WARP for navigational aid buoys into large floating multi-megawatt power plant, designated e-Sea WARPs. (previously referred to also as Spar-WARP or WARP Power Spar) Figure 8 shows a configuration with tension leg mooring which may be applied for operation in any depth water.

A basic application of e-SEA WARP units may be in conventional offshore wind farm manner along coastlines near energy centers such as cities and other population centers. This would be not unlike the offshore wind farms being deployed in the North Sea and Baltic by European firms using large rotor windmills. The only difference is that e-Sea WARP units may be more easily assembled in shipyards, towed/floated and secured to their respective sites which can be well removed from coastal view and with access to higher winds in any deeper water locations. Such offshore distributed power systems may also improve energy security. This stems from both the perspective of less dependence on imported energy as well as less vulnerability to terrorism when compared with large centralized power plants.

Another application may be for providing naval facilities with power and guarding of naval installations and country coastlines. e-Sea WARP units may be used for monitoring shipping, or use in countering subversive terrorist acts or military attacks including submarine monitoring and nap of the earth cruise missile attacks. e-Sea WARP systems may be equipped with highly sophisticated radar, sonar and other specialized monitoring and communications equipment as well as battle station weaponry to carry out their missions. For example, pumped lasers and the like may be located onboard and these could draw on megawatts of both active and/or stored energy onboard e-Sea WARPs. Storage is intended to be in the form of hydrogen gas within the floatation members of each e-Sea WARP system. Such sentries may be an effective complement to other Navy and Coast Guard units.

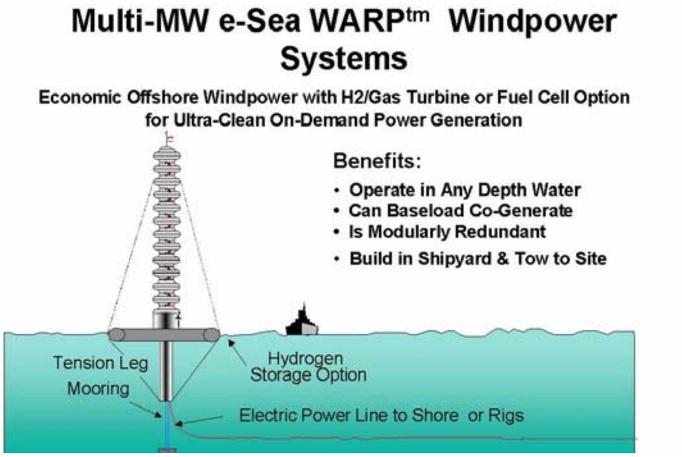


Figure 8. e-Sea WARP Power Systems Can Be Flexibly Tension Leg Deployed & Operated in Any Depth Water (*not to scale*)

e-SEA WARP SYSTEMS BENEFITS & COST EFFECTIVENESS

The features and benefits are discussed below of proposed e-Sea WARP systems in relation to conventional big bladed windmills used in offshore sites.

Reasonable land-based windmill sites have mean wind speeds of about 13 to 17 mph. By comparison, typical offshore annual mean wind speeds range from 15 mph to more than 20 mph at 10 meter (33 ft.) reference height for sites about 10 to 50 km (6 mi. to 30 mi.) offshore [19-21].

Production The modular e-Sea WARP systems design, contrary to large rotor windmills, is ideally suited for cost effective volume production in shipyards. This results from its few discrete, small, standardized sub-components and modular sub-assemblies. This system design additionally requires very low manufacturing capitalization. Production is easily deconstructed into the small, standard modules that can be aggregated rapidly to define the overall power plant given the site specific energy needs and wind resource characteristics. Figure 9 illustrates estimates of a small 2 megawatt (MW) e-Sea WARP unit presuming only 2 meter wind turbine rotors. For analysis purposes, a site with 8.8 m/s (~20 mph) mean wind speed was assumed. Estimates are based on codes similar to that found in the web site: http://www.warp-eneco.com including also floatation subsystem hardware costs.

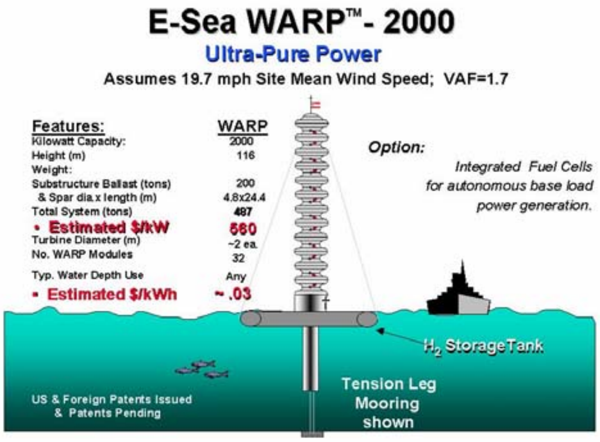


Figure 9. Estimated physical characteristics, cost and cost of energy of a 2 MW e-Sea WARP (based on Estimator code similar to found in WEB SITE: http://www.warp-eneco.com)

For the purpose of estimating a relatively small capacity e-Sea WARP configuration, a tested module rotor-to-toroid diameter ratio of 0.42 was used with 2-meter (6.6 ft.) diameter rotor wind turbines. Maximum module diameter is then about 8.8 meters (29 ft) and internal access 'waist' diameter is 4.8 meters (15.7 ft). No co-generating integral power system option was considered.

30 twin WARP turbine levels were estimated to be required with a nominal 1.7 velocity amplification factor and rated wind speed factor of 2.4. Each turbine was rated at about 35 kW on average. With a ~10 m (30 ft) base over sea level, the height of the system above sea level was determined 91 m (~300 ft).

To determine the floatation spar size, the approximate weight of the above sea level WARP power plant was calculated to be about 80 tons. The required size of the below water spar buoyancy tank, to support the 80 ton WARP and its 25 ton, 1.27 cm (0.5 in.) thick wall tubular steel base, consists of a steel tube 4.4 m (~15 ft.) in diameter and over 21 m (70 ft.) long. The spar tube diameter was chosen to be coincident and mate with the core support tower of the WARP modules. Different spar tube aspect ratios are possible to meet other site criteria such as water depth limitation, and optional hydrogen storage and potential naval operations equipment.

For survival stability with some tilt angle compliance, the required ballast of concrete in the base of the spar buoy was calculated to weigh about 160 tons for a total e-Sea WARP system weight of about 300 tons.

The naval architecture firm of Han Padron Associates, Inc. (HPA), Houston, TX, now a part of ABB Lumus, a leading deep water oil platform design firm, corroborated the preliminary analysis. HPA was also responsible for recommending the elegantly simple and cost effective tension leg mooring configuration. The latter has been successfully used on numerous oil drilling platforms that require exceptional platform stability for drilling purposes not needed for an e-Sea WARP wind power plant.

A sanity check on cost can be applied using a unit costing approach. Presuming an average cost of 0.9/kg ($2/lb) to $1.36/kg ($3/lb) of system weight, over half of which is inexpensive concrete ballast in this case, results in a capital cost in the $400/kW to $600/kW range and cost of energy in the range of about $.02/kWhr to $.04/kWhr with a discount rate of 9% and annual maintenance cost of 2% of capital cost. This unit cost compares well with unit cost of other large and more complex marine structures such as tankers which are known to cost between $1/lb. to $3/lb and which are typically not volume produced. Such costs reflect US rates. Lower labor rate regions may benefit since a majority of e-Sea WARPs is comprised of commodity structures.

Deep Water Siting Another fundamental benefit of e-Sea WARP systems is their ability to be located in any depth water due to inexpensive and stable floatation means. This expands offshore siting application dramatically with access to excellent wind sites.

However, the question may arise: Why not also simply mount large rotor wind turbines on floatation structures such a spar buoy? Several innate drawbacks exist for large rotor windmills relative to an e-Sea WARP.

Loads & Dynamics Contrary to an e-Sea WARP, which has a tower distributed load with guy-anchor options to any point along its tower, a conventional windmill has high overturning moments due to apex-concentrated point loading. A large rotor windmill in floatation mode also has high inertial and metronome-type dynamic loads because of large rotor head weight concentration on top of its tower. The large rotor inertial loads, aeroelastic limits, and precessional forces are inherently absent on an e-Sea WARP. The inertial loads and aeroelastic blade behavior of a large bladed conventional windmills can be especially problematic under icing or lightning strike generated imbalance situations, as well as under heavy sea wave action. This can lead to unstable and destructive dynamics. The yaw precessional forces of a big diameter windmill rotor, which tend to face the rotor askew to the wind, are unavoidable, and would be costly to restrain under simple buoyancy support. These forces are absent on an e-Sea WARP design with its small twin rotor assemblies at every level.

Icing Icing can be critical concern at sea in the colder regions of the world. e-Sea WARPs can have inexpensive built-in capability to anti-ice or de-ice through both active internal envelope self-heating, which may be supported by gas turbine or fuel cell operation, as well as passive solar heating characteristics. Its typically thin, yet exceptionally strong, and smooth compound curve fiber reinforced plastic (FRP) aerodynamic skin, properly coated and colored, can alleviate snow and ice build-up plus transmit internally generated heat for anti-icing.

Pack ice at sea can have severe impact on structures. Known to have turned over lighthouses, pack ice can give rise to heavy ice formations and pressure loading on any structure. Because this is only a problem for shallow water installations, this should pose no threat to e-Sea WARP installations that are expected to typically operate in waters deeper than 6 meters (20 ft) [19].

Assembly & Deployment Assembly and site installation is yet another benefit for e-Sea WARP systems because they can be readily assembled in shipyards or on-site without need for large rigging. They may be towed to site like oil platforms. Furthermore, only labor of low to moderate skill and cost is required for assembly and erection of a majority of a e-Sea WARP. This cuts cost in contrast to comparatively complex and costly installation procedures needed for today's large bladed windmills, particularly in the offshore. Assembly and erection of large rotor heads on top of tall towers requires high and costly skill level and major rigging equipment.

Serviceability & Availability Serviceability also favors e-Sea WARP systems since small man-sized turbines and equipment is readily accessible internally. The presence of many robust commodity turbines and associated sub-assemblies also greatly increases the probability of high system availability in the event of outage of any one module.

Offshore e-Sea WARP Systems with Co-Located Hydrogen Fueled Gas Turbines or PEM Fuel Cells

An assessment was made of e-Sea WARP cost effectiveness with co-located and co-generating power systems such as gas turbines and fuel cells to provide on-demand power using wind power generated stored hydrogen. Gas turbines are relatively low in capital cost (~$500/kW) but may require more maintenance and have a lower efficiency. Their operation with hydrogen fuel has already been effectively demonstrated by several aerospace firms [22] and presents no unusual technical challenge for environmentally clean power production. Fuel cells are expected to be the "battery" of choice in the future having effectively no moving parts. PEM fuel cells in particular are also attractive since they can serve both an electrolysis function for hydrogen generation as well as provide power from stored hydrogen in an instant. The higher capital cost of fuel cells, currently in the $4000/kW range, over gas turbines is expected to diminish in the foreseeable future and drop into under $1000/kW [23]. This would be particularly true if produced in quantities along with the wind power units.

e-Sea WARP systems can be realistically sized from a few megawatts capacity to over 10 MW and more due to its high strength modular construction. Integral gas turbine units can easily be matched to any size WARP unit and integral PEM fuel cell units can also be modularized to meet and match wind power capacity.

When excess wind electricity is available, electrolysis may be used to generate hydrogen. This process is typically 85% to 95% efficient (~85% if H_2 is compressed). The hydrogen can then be safely stored on the typically unmanned and remotely operated e-Sea WARP systems. The hydrogen would subsequently be converted to electricity when insufficient wind exists to meet grid load needs or be on stand-by for naval/coast guard missions, if so configured. The relatively high efficiency and response characteristics of fuel cells make them ideal to come on line as wind power drops off. Operational control and dispatch strategies can be modified and optimized for most profitable or best response operation depending on site renewable resources availability, energy demand, energy pricing and so on.

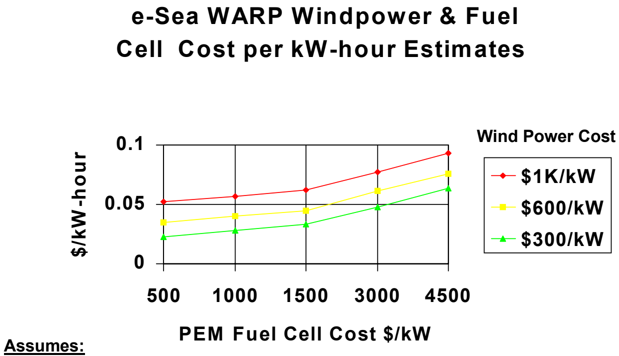
The “round trip” efficiency of electricity into producing hydrogen via electrolysis and subsequent re-use of this hydrogen through a Regenerative PEM fuel cell back to electricity is estimated at 40%. A similar “round trip” efficiency for a gas turbine with electrolysis for hydrogen is estimated to be below 25% to 35% [24-25]. Regenerative PEM fuel cells, therefore, have roughly 25% better hydrogen energy throughput.

Operational Strategy & Assumptions

The estimated complementary co-generation plant capacity of gas turbines or fuel cell power (kW) for an e-Sea WARP (wind farm or otherwise) need only be a fraction of that of the windpower system power capacity. This is because guaranteed delivery of baseload (on-demand) power is taken to be the average capacity factor of the wind power plant (typically in the 25% to 30% range, although it may be higher at sea sites) for meeting load demand. Output may exceed this capacity with wind generated electricity alone at times of higher winds, wherein it can opt to either deliver and sell it to the grid or use it for hydrogen production. During periods of shortfall of on-demand capacity from the wind, assuming this capacity is needed to meet load, or when peak capacity is required, stored hydrogen is converted by fuel cells or gas turbines to make up any such power capacity deficit and sent by submarine cable to shore [25]. The ability to meet peak capacity demand is especially valuable.

Given this operational scenario, a cost of energy assessment was conducted for a 100 count 2 MW e-Sea WARP units with either 200 PEM fuel cells of 250 kW capacity each or with gas turbines, details of which are reported in [24-25].

For the conservative case of fuel cells with e-Sea WARP, sensitivity to cost of energy (COE) results were determined for a variety of factors such as cost of fuel cells (ranging from today’s cost to future volume production cost) and cost of e-Sea WARP systems (from anticipated early limited production to volume production cost). See Fig. 10 for impact on COE. Parametric values were based on conservative estimated values of hydrogen storage cost and submarine cable installation cost. COE become about 10% lower when employing lower values of hydrogen storage and submarine cable installation costs of \$2.12/cu. meter of hydrogen and \$100,000/mile of cable respectively.
At today’s cost levels of up to \$4500/kW for fuel cells and a conservative \$1000/kW for the e-Sea WARP wind power system, the COE figures increase to about 9 cents per kilowatt-hour. Even at this level of COE, which does not reflect expected volume production cost of e-Sea WARP and fuel cells, the promise of ultra-clean renewable on-demand/ baseload power delivery warrants consideration for the benefits delivered.



Assumes:
- \$23/m^3 Hydrogen Storage Cost
- \$250K/mi Submarine Cable Laying
- 200 MW wind with 50 MW Fuel Cells
- 440 million kWh/yr Total Generation
- 9% Carrying Charge & 2% O&M

Figure 10. e-Sea WARP Windpower with Fuel Cell Power System COE Parametrics

SUMMARY & CONCLUSION

WARP advanced modular wind power systems, when built and deployed under serial production, are projected to provide cost of energy (COE) in the range of \$.01 to under \$.02/ kWhr when operating in excellent wind sites. An offshore version, the e-Sea WARP wind power system, may generate environmentally clean commercial grade electricity on-demand &/or serve naval/coast guard missions when operating in conjunction with integral hydrogen fueled gas turbines or PEM fuel cells. The opportunity for providing firm, ultra-clean, on-demand (~baseload) power at a cost of energy (COE) of about \$.02 to \$.03/ kWhr is possible under less than 200 MW level of volume production. The noted COE figures are based on typical US costs. This suggests that even more attractive costs are possible when e-Sea WARP systems are manufactured and deployed in countries with lower labor and material costs.

REFERENCES

[1] Spencer, P."Alternative Wind Power - A Next Generation Wind Power Technology?" RE-FOCUS-International Solar Energy Society; March/April 2002
[2] Makansi, J. "Amplify Wind Energy for Better Turbine Performance," POWER, pg. 12 ; Vol 142, No. 6 Nov./Dec. 1998

[3] Stover, D., "The Best of What's New – Science & Technology – Energy: - Wind Power Towers," Popular Science, December 1996.

[4] DeMoss , T., "Wind Energy 1.6 cents/kWhr?..Don't Pinch Yourself, it's Al Who's Dreaming," POWER ENGINEERING: Editorial column; September 1996.

[5 Brown, S., "Here Come The Pint-Size Power Plants – The Windmill's Narrow Niche," FORTUNE: [Industrial Management & Technology issue] April 1, 1996.

[6 Ostrow, S., Padalino, J. (Raytheon), Weisbrich, A. (ENECO), "WARP™: A Modular Wind Power System For Distributed Electric Utility Application," IEEE Transactions (Industry Applications), Vol. 32, No. 4

[7]. Ostrow, S. L., Padalino, J. (Raytheon), Weisbrich, A. L. (ENECO), "COE Projections For The Modular WARP™ Wind Power System For Wind Farms & Electric Utility Power Transmission," American Power Conference, Chicago, IL, 4/18/1995.

[8] Duffy, R.E.(RED Assoc.), Rigamonti, G. (Raytheon), Weisbrich, A. L. (ENECO), "WARP™-X: A Wind Power System For The 21st Century," American Power Conf., Chicago, IL, 4/26/1994.

[9] Liebowitz, B. "Verification Analysis of the Performance of the Toroidal Accelerator Rotor Platform Wind Energy Conversion System, Summary Report," NYSERDA, Project No. 431-ET-RER-82, Sept. 1988.

[10]. Duffy, R. E. (Rensselaer Polytechnic Institute), Weisbrich, A. L. (ENECO), Liebowitz, B. (New York State ERDA) "Wind Power Needle Application of the TARP Wind Energy Conversion System," 3rd ASME Wind Energy Symposium, New Orleans, LA, 2/12/1984

[11] Pucher, K. (Technical University, Graz, Austria), Weisbrich, A. L., (ENECO), "Computational Fluid Dynamic Assessment of a WARP™ Wind Power System," American Wind Energy Association Conference, Denver, CO, 6/23/1996.

[12] Rainey, D. L. (Rensselaer Polytechnic Institute/Hartford Graduate Center), Weisbrich, A. L. (ENECO), "WARP™ Technology For Low Cost & Environmentally Friendly Marine Based Wind Power Plants," British Wind Energy Association Conference (BWEA-20), Cardiff, Wales, UK , Sept. 2-4, 1998.

[13] R. E. Burns (National Regulatory Research Institute) A. F. Rhodes (WAT, Inc.), Weisbrich, A. L. (ENECO), "WARP™ : A Renewable Solar/Wind Power System for the New Millennium," POWER-GEN Conference, Orlando, FL Dec. 9-11, 1998.

[14] Olson, P. & Dr. Rainey, D. L. (Rensselaer Polytechnic Institute/Hartford), Weisbrich, A. L. (ENECO), "WARP™ Solar/Wind Power: Green, User-Friendly & Cost Effective for the New Millennium International Power Markets," American Power Conference, Chicago, IL, Vol. 61, 4/6/1999.

[15] Rainey, D. L. (Hartford Graduate Center), Weisbrich, A. L. (ENECO), "Mass Customization of WARP™ Wind Power Plant Design & Construction," American Power Conference, Vol. 59, 1997.

[16] Burns, R. E., Esq. (National Regulatory Research Institute), Dr. Rainey, D. L. (Hartford Graduate Center), Weisbrich, A. L. (ENECO), "Resolution of Critical Environmental Issues With WARP™ Wind Power Systems," American Power Conference, Vol. 58, 1996.

[17] Eliasson, Baldor, (ABB Corporate Research Ltd.), "Renewable Energy: Hydro, Wind, Solar, Biomass, Geothermal, Ocean-Status & Prospect," 1998, ABB, Baden, Switzerland

[18] Weisbrich, A. L. (ENECO), Rhodes, A. F. (SFA), "WARP™ Wind Power Technology for Offshore Oil & Gas Operation and Navigational Aids," Proceedings of the Offshore Technology Conf., Houston, TX , 1997.

[19] Hardell, R. (SIKOB AB), Ljungström, O. (FFA, the Aeronautical Research Institute of Sweden), "Offshore Based Wind Turbine Systems (OS-WTS) For Sweden – A System Concept Study," Wind Engineering, Vol. 3, No. 1, 1979.

[20] Heronemus, W. E., (University of Massachusetts) "Power from the Offshore Winds," Marine Technology Society, Sept. 1972.

[21] Kilar, L.A., Chowaniec, C. R., (Westinghouse Electric Corp.), "Technical and Economic Assessment of Offshore Wind Energy Conversion Systems," Final Report for DOE Contract No. E(49-18)-2330, 3/1978.

[22] Shum, F. and Moone, M. (Pratt & Whitney Canada), Kluyskens, D. (Hydro-Quebec), Cohen, J. (United Technologies Research Center) "Hydrogen Fueled Low Nox Combustors for Gas Turbine Engines," Combustion Canada'96, Ottawa, Canada, June 5-7, 1996

[23] Lovins, Amory B. & Williams, Brett D. (Rocky Mountain Institute), "A Strategy for Hydrogen Transition," 10th Annual U.S. Hydrogen Meeting, National Hydrogen Association, Vienna, VA, 4/7/1999.

[24] Gordes, J. N. (Environmental Energy Solutions), Weisbrich, A.L. (ENECO), Rainey, D. L & Olson, P.W. (Rensselaer Polytechnic Institute), "Offshore WARP™ Wind Power with Integral H2-Gas Turbines or Fuel Cells: Leaving the Fossil Age At Warp Speed for a First Step to a Hydrogen Economy," OWEMES 2000 (Offshore Wind Energy in Mediterranean and other European Seas) Conference, Syracuse, Italy, April 13-15, 2000

[25] Smith, W. (Proton Energy Systems), Rainey, D. L. (Rensselaer Polytechnic Institute), Weisbrich, A.L. (ENECO Texas LLC), Weisbrich, G. J. (ENECO TX); "Fuel Cell Augmented Offshore WARP™ Wind Power: A Proposed Step to a Hydrogen Economy," PowerGen Europe 2001 Conference, Brussels, Belgium, May 30, 2001.