Fuel Cell Augmented Offshore WARP^{tm} Wind Power: A Proposed Step to a Hydrogen Economy

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ABSTRACT

Environmentally clean and green energy is becoming a requirement of electric power delivery systems. Renewable energy has been cited as a potentially excellent means for generating hydrogen and, hence, forming a basis for creating a hydrogen economy. Major barriers to realizing a hydrogen economy, however, have been the expected large infrastructure transformation required and safety concerns in handling and storing hydrogen, plus the availability of widespread cost-effective renewable power systems. Wind power has been shown to be a good means for generating clean and relatively low cost power, however, only on an intermittent and limited siting basis. An advanced low cost and patently unique modular wind power technology, designated a Wind Amplified Rotor Platform (WARP^{tm}) System, has been developed which projects extraordinary economic and technical advantages and benefits over current windmill designs. A widely applicable marine offshore version of WARP, the Spar-WARP^{tm}, is proposed to operate in any depth water and include integral PEM fuel cells operating on wind system generated hydrogen for economical ultra-clean ***on-demand*** power delivery. Hydrogen may thereby be safely generated with wind energy, be stored and re-converted to electricity on these offshore platforms by fuel cells and brought to shore by submarine cable. This may eliminate a special, widely dispersed hydrogen infrastructure because, in essence, the existing electric utility power transmission and distribution network then serves as a "hydrogen by wire" infrastructure. Large environmental and economic benefits may be realized with this approach whereby Spar-WARP^{tm} systems can provide baseload electricity from

normally excellent wind sites at sea, yet not far from shore. A potential spin-off benefit and commodity from Spar-WARP^{tm} systems may be the generation of pure water as a result of combined wind power and fuel cell operation.

General systems description, performance, cost and cost of energy projections are addressed for this proposed environmentally ultra-clean, on-demand, renewable power system which, upon development and serial production, may provide energy below \$.02/kWh to under \$.04/kWh , depending on wind, based on US hardware and labor rates.

INTRODUCTION

For the reason of the intermittent nature of renewable forms of energy such as wind and solar energy, such systems have been perceived as limited in application. Use of hydrogen as a fuel for power generation has also suffered acceptance mainly because of overblown historical incidents such as crash of the Hindenburg airship, and the anticipated high infrastructure transformation cost from petroleum to hydrogen. A further barrier to widespread use of systems such as photovoltaic systems and fuel cells, which require hydrogen, is their high initial capital cost. Wind power systems, however, have become increasingly competitive with conventional fossil power. However, current large bladed rotor configuration windmills still have a variety of nagging issues. These issues include occasional blade failures, gearbox failures, large land sprawl and associated zoning restrictions, visual detraction, noise, telecommunication interference, bird kill, and high susceptibility to lightning damage. For reasons of land use, failure 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 solving some of the stated problems, the limitation of large rotor windmills to shallow waters and costly structural and maintenance issues are impeding full widespread potential of offshore windpower from being realized. The recently internationally patented modular Wind Amplified Rotor Platform (WARP^{TM}) wind power system design, as will be described, can avoid virtually all the stated problems of today's windmills and is projected to have lower cost as well.

The WARP^{TM} Wind Power System

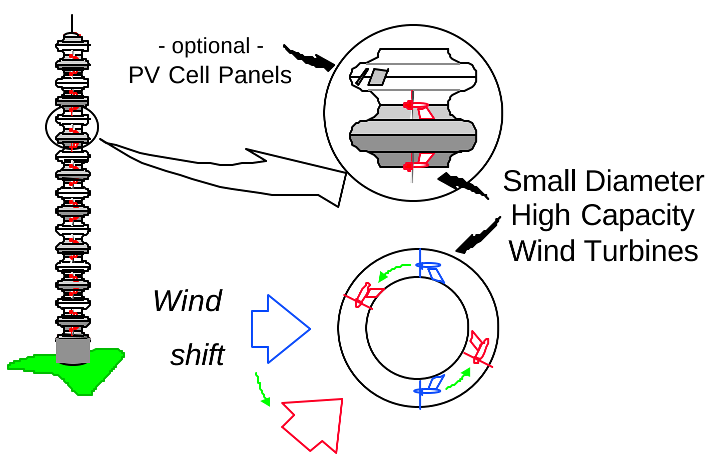


Fig. 1a. WARP Modules Amplify Wind to 80% & Yaw into Wind

Nevertheless, the WARP design can draw on much existing excellent windmill research and development (R&D) 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 windmill rotors and gears due to a history of past failures of such machines, which have included the first large diameter windmill, the 1.2 MW Putnam turbine on Grandpa's Knob, VT, USA built in the 1940's, and have continued into the current era of utility scale wind turbines built by US Windpower, GE, Boeing, Hamilton Standard, NEG-Micon, Zond and others. WARP designs have no large rotors and/or gears.

BASIC WARP™ WINDPOWER TECHNOLOGY DESCRIPTION

The Wind Amplified Rotor Platform (WARP™) advanced windpower system design consists of stacked wind amplifier modules with a multiplicity of small, simple and high capacity and high reliability commodity wind turbines integrated thereon, differs dramatically from today's single, large-rotor diameter windmill design, with massive rotorhead assembly apex mounted on a tower. Yet this patented design draws heavily on the latest technology developments of today's conventional windmills, but without the inherent risks and drawbacks of the latter. WARP is being recognized as a breakthrough in wind power technology because it can synergistically avoid a myriad of liabilities experienced by today's conventional large bladed windmills (Ref. 1-5).

As illustrated in Fig. 1a, b & c, the WARP system configuration consists of stacked toroidal amplifier modules peripherally mounted on a simple core tower (Ref. 6-10). These modules can incorporate at each elevation level in their peripheral flow channels, about 180 degrees apart, a pair of small diameter, high capacity, but low cost, wind turbines *requiring no step-up gearbox*. Such turbines can exhibit high reliability comparable with that of aircraft propellers, which have hundreds of millions of passenger miles of successful operation history. WARP systems can be easily customized to any power capacity by virtue of the modular amplifier building blocks, also known as Toroidal Accelerator Rotor Platforms (TARPs).

The WARP module aerodynamic building blocks can amplify on average by over 150% to 180% the ambient wind speed to the turbines. 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 improves economics substantially (see Fig. 2).

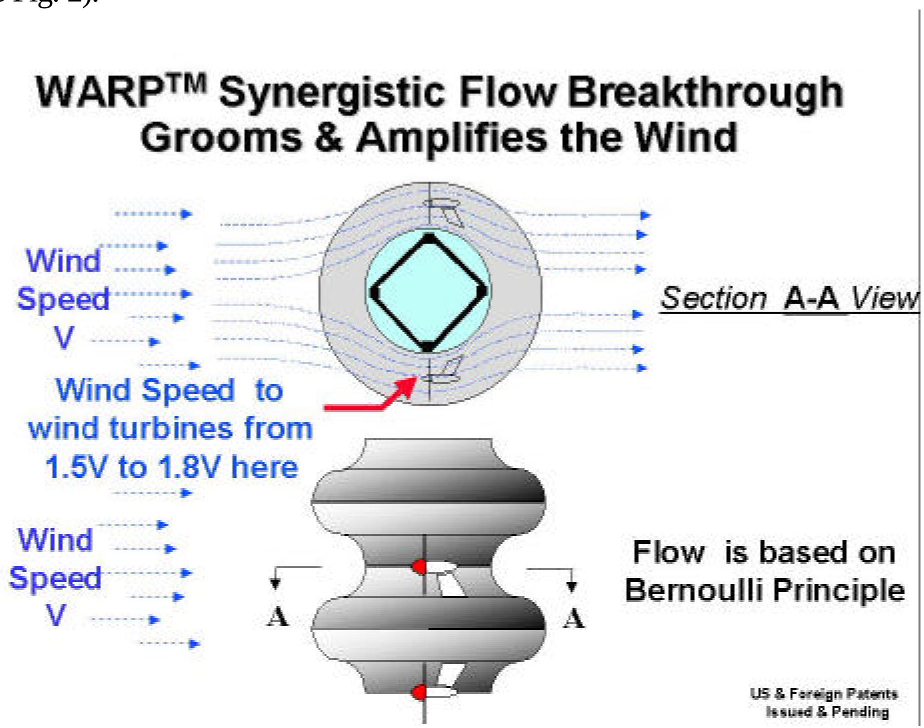


Fig. 1b WARP Module Flow Enhancement to Turbines is based on Bernoulli Principle

Specifically, WARP wind amplifiers, aside from increasing wind energy density, provide other functional and 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 complementing each yawing module. WARP can be designed to accommodate many types of wind turbines to recover the high density and high-energy wind flow fields. Fortuitously, near optimum WARP wind turbine rotor RPM tends to match available generator speeds, eliminating the need for gearboxes.

Another extraordinary feature is that WARP turbine generators can be internalized to the module. This can isolate rotor thrust loads from the generator. It also allows optimizing rotor to generator speed matching via introducing very small RPM step-up, plus provides ready internal access to the generator for ease of servicing. The ability to link a set of rotors to a single internal generator opens further cost and operational benefits.

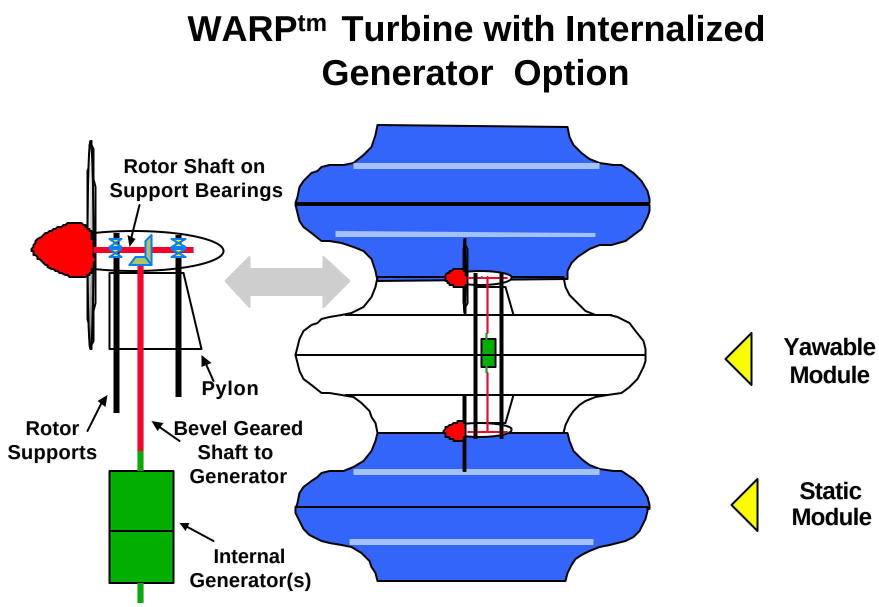


Fig. 1c Internal WARP Generators Can Provide Added Optimization, Access & Cost Benefits

Analyses, Wind Tunnel & Field Tests

In excess of $1 million in analytical and test R&D has been carried out on WARP to date in conjunction with Rensselaer Polytechnic Institute (RPI) and the New York State Energy Research & Development Authority (NYSERDA), and other independent organizations. The technology has undergone convincing analytical assessment, including computational fluid dynamic (CFD) analytics, 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 showed between 20% to 50% increase over ambient wind speed to the 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, this translated into more than 3 times the power over a wind turbine in the free air. This was clearly enough to encourage pursuing the concept. Initiation of subsequent licensing discussions in Europe led to commissioned computational fluid dynamic (CFD) investigations at the Technical University of Graz, Austria (Ref. 11). These investigations in 1996 revealed that tall stacked arrays of WARP modules could produce VAF of 1.7 to 1.8 on average of the free stream wind speed. This conforms to relative maximum power of about 4 to 5 times that of the turbine in free air. WARP performance is 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 (Ref. 6-10) co-authored by ENECO and Raytheon, and as proposed by Raytheon to the NREL of the US Dep't. of Energy.

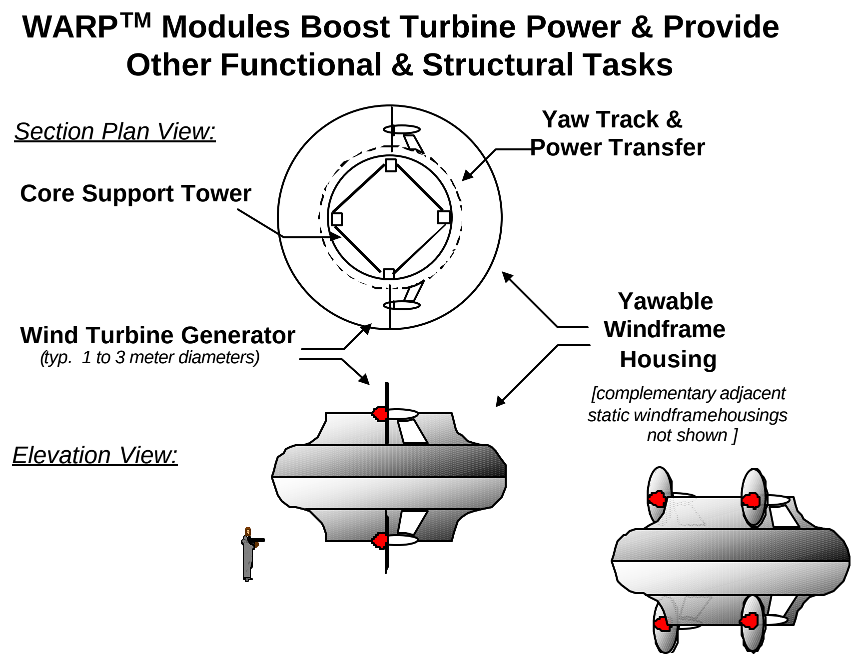


Fig. 2 WARP Modules Can Amplify Free Wind 80% & Have Multi-Tasking Features & Benefits

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

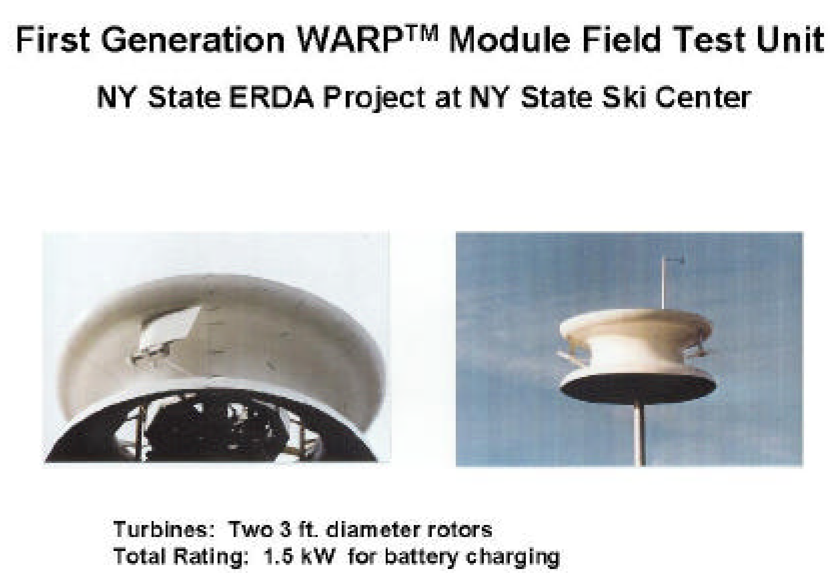


Figure 3. First Generation Test Module with Turbines Replicated Wind Tunnel Flow Characteristics

The test installation had 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 configuration isolated wind tunnel test model.

Due to siting limitations and restrictions, the unit tower had to be closely positioned near the edge of a cliff that faced the prevailing northwest winds. The prevailing winds impacted the module at a roughly 45 degree upwash angle and, hence, into the module flow channel. As a result, the flow amplification in the channel and performance of the wind turbines therein were compromised under these unusual upwash flow conditions. Furthermore, in January of 1996 an unfortunate disastrous force majeur wind storm occurred near the end of the project while waiting for properly high and relatively 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 regions of Ulster and Delaware, NY to be officially declared a disaster area. The WARP module, 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. Nevertheless, with the module having survived this 100-year wind storm, it demonstrated the structural resiliency and inherent strength of the toroid module configuration although it was made of only one eighth (1/8) inch thick spray-up fiberglass aerodynamic skin panels supported internally by a steel frame at 3 points about the module periphery. In a prior storm, the unit also successfully demonstrated fail-safe module yaw parking (i.e.; shut down) when a flaw in a vendor's rotor hub caused it to throw a blade.

Subsequent to termination of this test program, ENECO embarked on major patented cost reducing and performance enhancing design improvements. These resulted in improved application performance, versatility, and lower cost, furthering its competitive energy cost relative to that reported in prior IEEE Transaction Journal and American Power Conference technical papers. (See Figure 4).

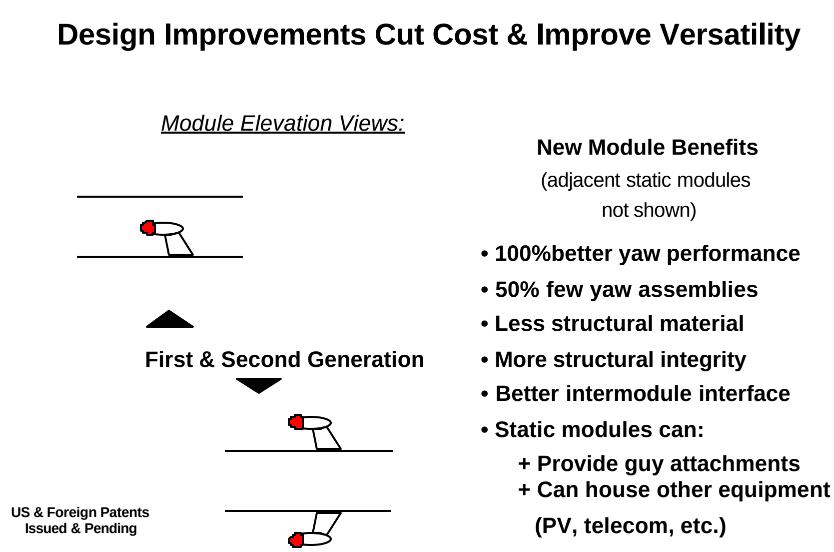


Figure 4. WARP Design Improvements Cut Cost & Enhance Performance Further

As noted in Figure 4, patented improvements will reduce system cost dramatically, give better performance, add to the structural integrity of the system and provide the basis for enhanced system application versatility. The latter includes an option to incorporate photovoltaic subsystems for synergistic solar energy capture, as well as guy attachment means and housing suitable for wireless telecommunication equipment, among others.

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 over the rotor disc area, depending on configuration and stacking aspect ratio, (i.e.; Velocity Amplification Factor (VAF)=1.5 to1.8) (see Fig. 5 & Ref. 11). For example, *the impact of a 65% wind speed-up 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, and by gearless direct drive and turbine tip shrouding. The gearless direct drive and shrouded turbines eliminate and reduce gearing and tip losses, respectively. WARP capture area can therefore be less than for comparable power conventional windmills; hence, WARP can attain higher system efficiencies.

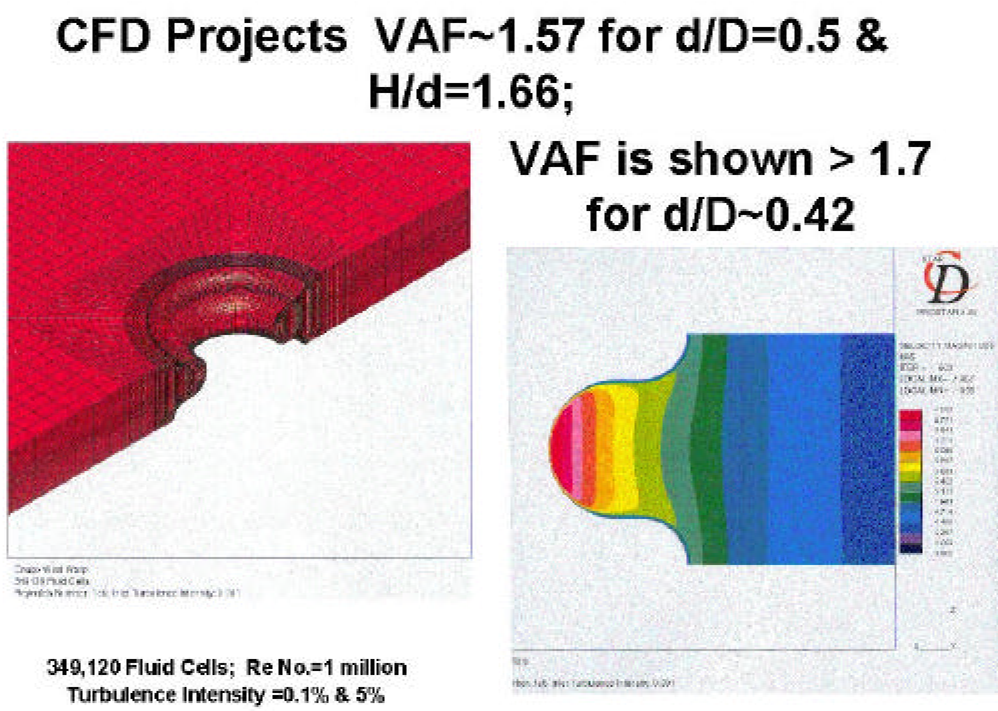


Figure 5. CFD Analyses Show WARP Modules Can Amplify Wind Speed over 1.7 Times Free Wind

Horizontal axis wind turbines of 1 to 3 meters in diameter (d) are envisioned for commercial electric utility scale WARP systems. For such size turbines, rated capacities of between 10kW to 50 kW per WARP rotor may be incorporated, depending on site mean wind speed and module height. Wind turbines on WARP are designed as a commodity, not as a complex and costly focus as are giant rotor-heads on conventional windmills. *WARP power tower capacities from kilowatt levels to multi- megawatt levels can be readily assembled and site tailored.* Contrary to single large rotor-head windmills, *another major benefit with the WARP module building block design approach is that expensive rotor re-design and re-tooling is eliminated when new capacity systems* are desired. Instead, multiple WARP modules, each having common rotors, common stock generators of specified capacity, can be stackarrayed on a common tower to achieve desired system power capacity. Figure 6 illustrates parametric curves of approximate 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 6 ft. (~2 m) and the VAF is 1.7 in the specified module configuration.

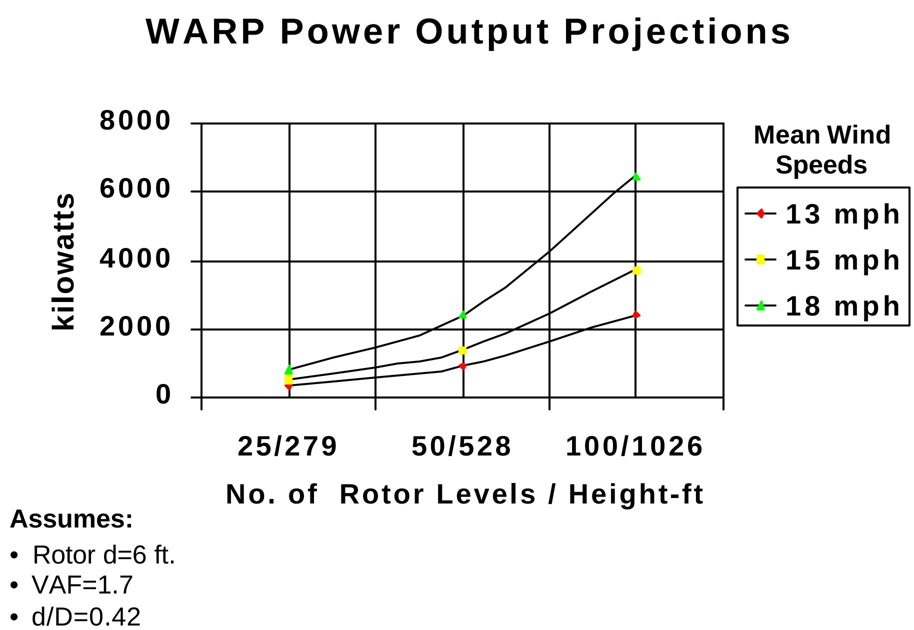


Fig. 6 WARP Power Capacity Can Be Easily Customized with Module Number

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, particularly with the significant post-1996 configuration improvements (Ref.12, 13 & 14).

Mass production has long been recognized as an effective means of reducing a product's unit cost (Ref. 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 a *single shape panel can* *form the entire exterior aerodynamic structure of a WARP system*, hence, a sizeable cost percentage of the system. This, along with repetitive tower and turbine sub-assemblies, lends itself to cost effective system via mass production.

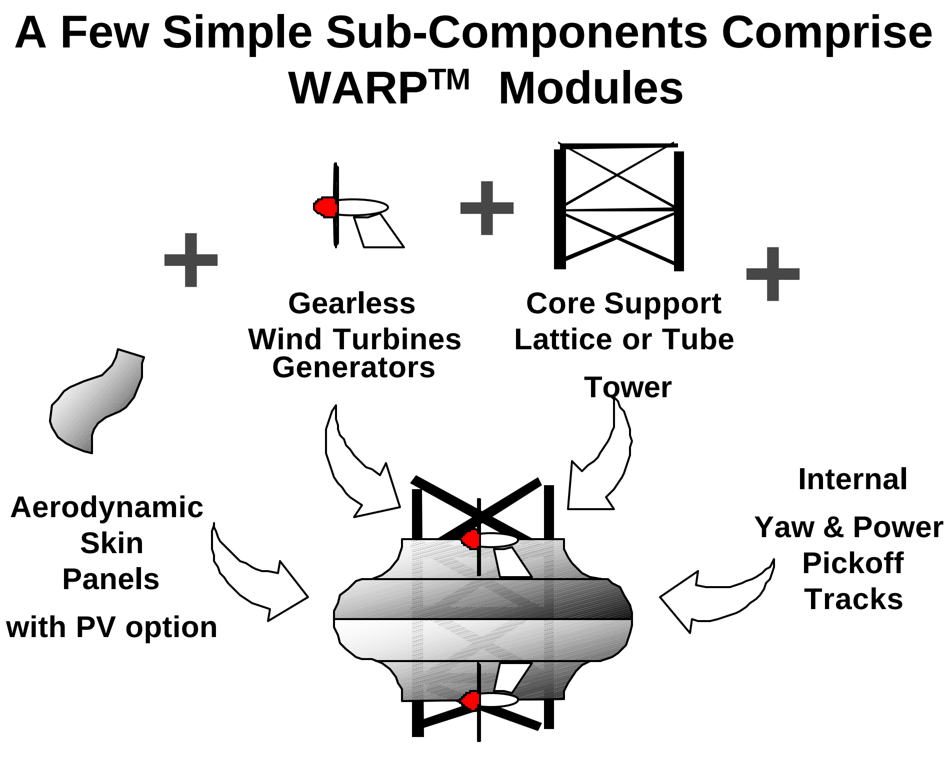


Figure 7. WARP is Readily Volume Produced for Low Cost

WARP Environmental Benefits

WARP environmental benefits are obviously significant when compared to traditional fossil-fired power plants. However, WARPs also have improved features relative to traditional large diameter rotor windmills. Despite their non-airpolluting energy generation, today's typical large bladed windmills still have shown nagging environmental problems, safety risks and liabilities. These include large unsightly land sprawl, bird kill, noise, blade failure, effluent from hydraulics or gearbox transmissions, destruction from lightning damage, 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 Ref. 16.

WARP with Fuel Cell Incorporation Option

WARPs can internally co-locate and co-generate with other power systems. These can include fossil-fueled gas turbines, microturbines, diesels and fuel cells. Also, a WARP system may uniquely and economically add ~10% more electric power capacity to its windpower capacity by integrating photovoltaic cells (PV) to common WARP structure which can reduce current high PV costs substantially. Since 50% of the cost of conventional stand-alone PV systems typically resides in PV module structural support (25% is cell cost) (Ref. 17), “piggybacking” PV cells or modules on WARP amplifier modules, either embedded on aerodynamic structure panels or behind translucent 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, "baseload" or on-demand power output capability, WARP systems are proposed to co-operated with synergistically co-located PEM fuel cells within its internal tower housing. The intent is to operate fuel cells on hydrogen fuel generated by excess WARP wind power. When the wind turbines are operating below demand capacity, fuel cells come on line to pick up the required balance of demand power. This approach would permit ultra-clean 'green' baseload power to be generated. However, proper siting for such operation is important. An ideal site is the marine offshore due to typical excellent wind resources and because it eliminates many potential social/zoning (NIMBY) issues which can be an impediment to any systems deployment. Europe has initiated this trend to sea for windmills for this reason.

OFFSHORE WARP SYSTEMS BENEFITS & COST ESTIMATES

Modular WARP systems lend themselves for adaptation to many common host structures. Among host structures investigated for WARP integration have been offshore navigational buoys and oil platforms for which WARPs show excellent fit (Ref. 18). This prompted a conceptual scale up of a WARP navigational aid spar buoy into a large floating multi-megawatt power plant, designated a Spar-WARP. Figure 8 shows a simple configuration with tension leg mooring, which allows stable operation in any depth water.

Attractive features of a Spar-WARP are noted below when compared with conventional large windmills used in offshore sites.

Production

The modular 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.

Deep Water Deployment

Another fundamental benefit of Spar-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 a large rotor windmill relative to a Spar-WARP.

Loads & Dynamics: Contrary to a Spar-WARP, which has a tower distributed load plus may even be guy-anchored 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 the tower. The large rotor inertial loads, aeroelastic limits, and precessional forces are inherently absent on a Spar-WARP. The inertial loads and aeroelastic blade behavior of a large conventional windmill rotor head 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 large windmill rotor, which tend to face the rotor askew to the wind, are unavoidable, and would be costly to restrain under simple buoyancy support only. Yet these will be absent on Spar-WARP with their small twin rotor assemblies at every level. For a buoy-mounted conventional windmill firm yaw restraint of the support buoy would be needed

Icing: Icing can be critical concern at sea in the colder regions of the world. Spar-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 fuel cell operation, as well as passive solar heating characteristics. Its typically thin, yet exceptionally strong, and smooth compound curve 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 Spar-WARP installations that are expected to typically operate in waters deeper than 6 meters (Ref. 19).

Assembly & Deployment: Assembly and site installation is yet another benefit for Spar-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 Spar-WARP. This contrasts sharply with the comparatively complex and costly installation procedures needed for today's large bladed windmills, particularly in the offshore. Assembly and erection of large, complex rotor heads on top of tall towers requires high and costly skill level and major rigging.

Serviceability & Availability: Serviceability also favors Spar-WARP systems since small man-sized turbines and equipment is readily accessible internally or externally. 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.

2 MW Spar-WARP Assessment

For the purpose of estimating system size and cost a 2 MW Spar-WARP configuration (previously called a WARP Power Spar (WPS) - Ref. 12, 13, & 14) was selected. A typical module rotor-to-toroid module 'waist' diameter ratio of 0.42 was used, similar to those in prior test configurations, with 2-meter diameter rotor wind turbines. Maximum module diameter is then about 8.8 meters and internal access 'waist' diameter is 4.8 meters. No PV or other integral power system option was considered initially.

Typical 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 20 mph and more at 10 meter (33 ft.) reference height for sites about 10 to 50 km (6 mi. to 30 mi.) offshore (Ref. 19, 20 & 21). For analysis purposes, a site with 18 mph mean wind speed was assumed.

For a 2000 kW capacity Spar-WARP, 30 twin WARP turbine levels were estimated to be required for 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). This compares with about 80 m (~262 ft.) height (tip of rotor) for conventional 500 kW windmills placed recently on shallow water foundations at Tuno Knob, Denmark.

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, possible hydrogen storage, etc.

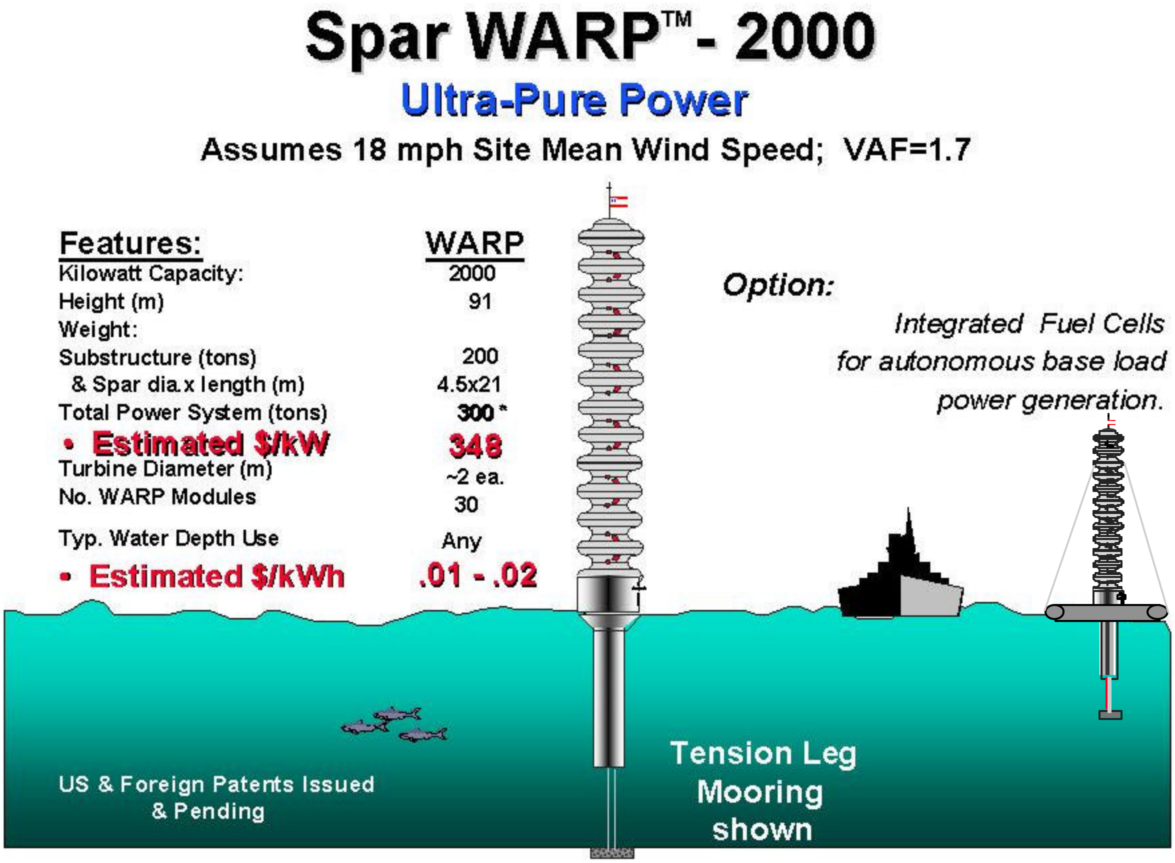


Figure 8. A Spar-WARP Power System Can Be Flexibly Deployed & Operated in Any Depth Water (*not to scale*)

The system has inherent built-in compliance to wind loads and allows a level of tilt angle under survival wind speed. For survival stability with some tilt angle, the required ballast of concrete in the base of the spar buoy was calculated to weigh about 160 tons for a total Spar-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 firms corroborated this preliminary analysis under review. HPA also recommended the elegantly simple and cost effective tension leg mooring configuration option good for even very deep water. The latter has been successfully used on numerous operational oil drilling platforms that require substantially more platform stability for drilling purposes.

The energy capture for this Spar-WARP was estimated at 4.8 million kWhrs/yr. Total capital cost of the unit, which weighs 300 tons, was estimated based on a conservative average $2 to $3 per pound of system weight, over half of which is inexpensive concrete ballast in this case. This compares well with 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.

With a conservative \$2 to \$3/lb system cost, the cost of energy (COE) for a single unit 2000 kW Spar-WARP system, given the noted wind, energy capture, a discount rate of 9% and annual maintenance cost of 2% of capital cost, is about \$.02/ kWhr to \$.04/kWhr. With a WARP serial production cost estimate of \$1/lb., a COE of about \$.01/kWhr can be realistically achievable at a system cost of about \$300/kW. Electric cable to shore and grid tie cost is an additional variable which gets allocated among many installed units. For example, for a 100 MW Spar-WARP windfarm 10 miles offshore and assuming \$100,000 per mile of cable installation, the added cost is expected to only be an additional \$5/kW to \$10/kW.

Offshore Spar-WARP Systems with Co-Located Hydrogen Fueled PEM Fuel Cells

As noted, the basic WARP system configuration, with its multiplicity of small robust commodity turbines, is particularly well suited for economic deployment and operation in the marine offshore environment. Once floated to site and secured to location/anchored, its internal housing and tubular spar buoyancy member(s) can multi-task to provide housing for other purposes and equipment.

Spar-WARP systems can be realistically sized from a few megawatts capacity to as much as 10 MW due to its high strength modular construction. Integral PEM fuel cell units are proposed to be included in modular units of 250 kW to 1 MW, depending on requirement with the host Spar-WARP system size.

Fuel cells can be made to operate on Spar-WARPs with hydrogen fuel produced by the WARP wind turbines at sea. When excess wind electricity is available, using the PEM fuel cells for the electrolysis process, hydrogen is produced. Electrolysis is typically 85% to 95% efficient (~85% if H_2 is also compressed). The hydrogen can then be safely stored on the typically unmanned and remotely operated Spar-WARP systems. The hydrogen can subsequently be converted to electricity when insufficient wind exists to meet grid load needs. 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 operation depending on site renewable resources availability, energy demand, energy pricing and so on. Stand-alone operation or connection to small grid systems may also be viable.

PEM Fuel Cells

Fuel cells, wherein proton exchange membrane (PEM) electrolyzer technology is a core component, can serve both as electrolysis units using excess wind energy to generate hydrogen, and as a power generator using stored hydrogen when load demand can not be met by wind power alone. The only by-product of the fuel cell is clean water vapor (a potential source of potable water). PEM technology has been used for decades to produce hydrogen and oxygen from water, for special life support systems like spacecraft and submarines. Although more efficient than traditional combustion engines in converting the energy in hydrogen to useful work, fuel cell cost is still considerably higher today due to their lack of volume production. Fuel cells also scale very well and have better operating and maintenance characteristics than gas turbines due to few moving parts. Currently, fuel cells cost about \$3000 to \$4500 per kilowatt while gas turbines cost about \$400 to \$500 per kilowatt. However, with volume demand and production of fuel cells, as with most systems, their cost is expected to drop significantly over time. Production ramp-up of fuel cells is expected in the near term for automotive use by firms like Canada’s Ballard Power Systems, and for static power units by firms like Proton Energy Systems, Plug-Power, the Fuel Cell Corp., ONSI and others. This is expected to drop to their cost into the \$500 to \$800/kW range, as noted in a recent Rocky Mountain Institute paper by Amory Lovins, et al (Ref. 23). Other projected fuel cell cost figures are \$400 per kW to \$1,500 per kW, the latter of which is referred to as a near term target number.

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%. This “round trip” efficiency for a gas turbine using hydrogen is estimated to be below about 25% to 35% in connection with an electrolyzer (Ref. 24). Regenerative PEM fuel cells, therefore, have roughly 25% better hydrogen energy throughput.

A potential valuable spin-off commodity from open cycle fuel cell operation on a Spar-WARP^{tm} is the generation of pure water as a result of wind powered electrolysis supplying hydrogen fuel to the fuel cells. This amounts to 0.741 pounds of pure water per kWh of energy generated by the PEM fuel cells, or about 1 gallon of water per 8 kWh. This could benefit places in need of clean water.

Operational Strategy & Assumptions

It is estimated that the complementary fuel cell power (kW) capacity for a Spar-WARP windfarm 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 windfarm (typically 25% to 30%) 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 to make up any such power capacity deficit and sent by submarine cable to shore (Ref. 25). The ability to meet peak capacity demand is especially valuable, yielding as much as five to ten times typical energy prices, as evident from California’s energy situation today.

The availability of offshore winds is typically considerably higher than on land. Furthermore, wind speed is accentuated and more abundant and steadier at elevation (versus nearer to ground) and these higher winds are accessible by tall Spar-WARP units. Calm periods are known to occur roughly only about 5% of time based on near shore data. It is assumed that the fuel cells need to operate only about 20% of time on average over the year. Hence, hydrogen storage needs are expected to be smaller than if the system were on land where lower winds exist. A novel and proprietary (undisclosed) hydrogen storage means is also assumed and reflected in the analysis. This storage approach is estimated to have lower cost per cubic meter of stored hydrogen than traditional stand-alone tankage cost. WARP tanks can serve both as system buoyancy members as well as hydrogen storage for reduced cost. However, the impact on cost of energy is minimal for cost changes in this part of the system.

Given this operational scenario and the following mass deployed system factor assumptions, the following renewable on-demand/baseload power plant cost estimate is made using 100 2 MW Spar-WARP units with 200 PEM fuel cells of 250 kW capacity each.

***Wind System*:**

Offshore Spar-WARP Windfarm Installed Capacity	200 MW
Spar-WARP Capital Cost	~$300/kW - $600/kW
Offshore Windfarm Capacity Factor	25% - 30%
Annual Wind Electric Production Potential	500 Million kWh/yr (500 GWh)
Cost of Wind Electric Energy	$.012 - $.022
(@ i=9%; O&M=1% - 2% of capital)	
Guaranteed Baseload Power	50 MW

Wind Electricity Diversion for Hydrogen Production *(may be very conservative for offshore wind regimes)*	100 Million kWh/yr

Complementary Power Systems Equipment & Capacity:

PEM Regenrative Fuel Cells (with electrolyzer)	50 MW
Capital Cost (based on volume production)	\$500/kW - \$1000/kW
O&M	1% -3% of Capital
PEM Fuel Cell (FC) Hydrogen Conversion Efficiency	~.45 to 50+%
"Round trip" Efficiency [wind electric ->H_2->FC electric]	~40% (assume 0.8*.50)
Pure Water Generation Option	0.741 lb/kWh
Hydrogen Conversion (energy produced/ m^3)	~1.25 kWh/ m^3 Hydrogen
Hydrogen Fuel Cost per kWh output / m^3- compressed	\$.04 =[\$.012*4.2kWh$_{in}$]/1.25kWh$_{out}$

Hydrogen:

Hydrogen Storage requirement estimate	24 hours at 50 MW continuous
Hydrogen Storage Containment cost/m^3 estimate	\$2.12/m^3 H_2 (*prop*.) - \$23/m^3 H_2
Required Electric kWh/1m^3 Hydrogen generation	3.16 kWh – 3.5 kWh or 4.2 kWh (w/ compression to 200 psi)
Hydrogen Generation Cycle & Use Cost/ m^3 H_2-estimate check:	
e.g. (\$.012/kWh wind elec.$_{in}$)*(3.16 kWh / m^3 Hydrogen$_{out}$)	~\$.038/ m^3 H_2-STP (uncompressed)
e.g. (\$.012/kWh wind elec.$_{in}$)*(4.2 kWh/ m^3 Hydrogen$_{out}$)	~\$.05/ m^3 H_2- compressed

Cabling to Shore: \$100,000 per mile

Site Location: ~10 miles offshore with 8.5 m/s to 9.5 m/s mean wind speed

On-Demand/Baseload Spar-WARP^{tm} System with PEM Fuel Cells

.

Capital Cost (CC):

Spar-WARP Wind Plant- 200 MW	\$ 60 Million (M)
PEM Fuel Cells – 50 MW (based on volume production)	\$ 25 M
Electrolyzers – 50 MW	*(included above)*
Hydrogen Storage – 50 MW for 24 hr. *=1.2 million kWh for conversion @ 1.25 kWh/ m^3 H_2 = 960,000 m^3 H_2*	\$ 2.0 M * - \$20M
Transmission Cabling to Shore Grid *10 Mi. @ \$100K/mile-\$250K/mi*	\$ 1 M – \$2.5 M

* proprietary storage means.

Annual O&M Cost:

Spar-WARP Wind Plant@ 1% of CC	\$ 0.6 Million
PEM Fuel Cell @ 1% of CC	\$ 0.25 M
Electrolyzers	*(included above)*
H_2 Storage & Cables @ 1% of CC	\$ 0.03 M

Capital Carrying Cost: i = 9%

Net Energy Production to Grid:

Spar-WARP Wind Electric	400 mil. kWh/yr
PEM Fuel	40 mil. kWh/yr
(100 million wind kWh/yr diverted for conversion per Fuel Cell) efficiency)	*(100 mil..* 0.40 round trip*
Total System:	440 mil. kWh/yr

Nominal Hybrid Ave. Efficiency:
A rough order of magnitude efficiency may be calculated assuming the wind plant generates 90% of grid delivered electricity at ~40% efficiency, while the fuel cells generates the balance at (40%)(90%)((50%)=18% total wind-to-electricity throughput efficiency.

Hybrid System Ave. Efficiency = [(.90)(.40) + (.10)(.18)]/1.0 = 0.38 or ~ 38%

This value is comparable to typical thermal plant efficiencies, but without pollutants.

Total System Cost of Energy: **$.020**

Wherein Cost of Energy (COE) estimates are based on the following basic expression:

$$\mathbf{COE} = \frac{\mathbf{i*CC + O\&M}}{\mathbf{kWh/yr}}$$

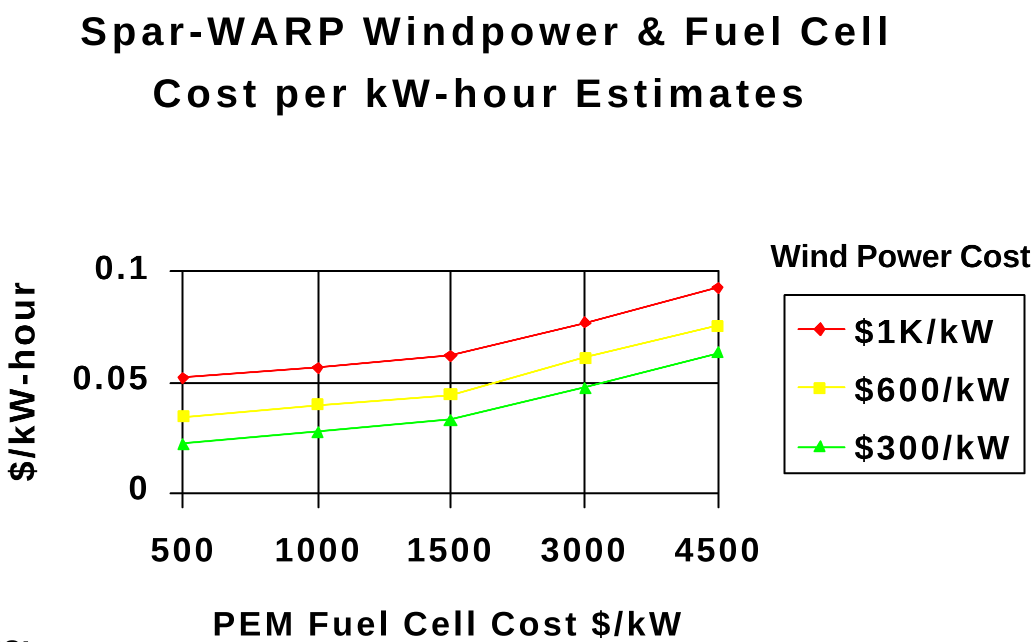
where, CC = summation of Capital Cost of respective sub-systems
O&M = Operating & Maintenance cost of respective sub-systems
i = capital carrying cost

With the noted lowest volume production economy of scope cost assumptions and the conservatively high values of hydrogen storage and submarine cable installation, Spar-WARP windpower systems operating with complementary hydrogen fueled PEM fuel cells are projected to achieve attractive energy cost at about 2 cents per kilowatt-hour. At 2 cents per kilowatt-hour, a 200 MW capacity offshore Spar-WARP wind farm with integral 50 MW capacity of PEM fuel cells is clearly an attractive power plant having firm 50 MW of ultra-clean, on-demand baseload power output capability.

To assess the sensitivity of results to varied factors such as cost of fuel cells (ranging from today's cost to future volume production cost) and cost of Spar-WARP systems (from anticipated early limited production to volume production cost), key cost parameters were varied to assess impact on cost of energy (see Fig.

9). Figure 9 parametric values are based exclusively on the most conservative estimated values of hydrogen storage cost and submarine cable installation cost.

These cost of energy (COE) figures become about 10% lower when employing the lower values of hydrogen storage and submarine cable installation costs of \$2.12/m3 of hydrogen and \$100,000/mile of cable respectively.



Assumes:

- \$23/m³ 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 9. Spar-WARP Windpower with Fuel Cell Power System COE Parametrics

At today's cost levels of \$3000/kW to \$4500/kW for fuel cells and a conservative \$1000/kW for the Spar-WARP wind power system, the COE figures increase to about 9 cents per kilowatt-hour. Even at this level of COE, which in no way reflects volume production impact on Spar-WARP and fuel cell cost, the promise of ultra-clean renewable on-demand baseload power delivery warrants consideration for the benefits delivered. The financial, environmental and global health benefits derived from large scale deployment of such systems are projected to be very attractive. The latter two benefits may even be critical to today's world as we seek to be good stewards of our God-given creation.

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 \$.015/ kWhr when operating in excellent wind sites as may be found offshore. A proposed hybrid offshore version, the Spar-WARP wind power system, operating in conjunction with integral hydrogen fueled PEM fuel cells, is shown to offer an attractive opportunity for providing *firm, ultra-clean, on-demand* (baseload) power. Specifically, (COE) of about $.02/ kWhr is possible under volume production in the range of 200 MW of such an environmentally attractive marine-based offshore systems. Of importance is that the noted COE figures are based on US labor rates which tend to be high by global standards. This suggests that even more attractive COE (and associated return on investment) is possible when such Spar-WARP systems are manufactured and deployed in countries with lower labor cost. The latter is very viable because the majority of Spar-WARP systems is comprised of conventional structures. Such an environmentally super clean baseload energy supply system can form the basis of a hydrogen economy-by-wire via submarine electric cable to existing land based electric utility grid networks without need for any transformation of today's power system infrastructure. Pure water as a spin-off byproduct from a Spar-WARP wind power/fuel cell system operation is yet another potential benefit. The financial, environmental and global health benefits derived from large scale deployment of such systems are projected to be very attractive.

The key characteristics of WARP technology which can make this possible are:

Low Cost:

- Minimal capitalization requirement for manufacture of simple modular assemblies;
- Mass production of few small discrete parts;
- No costly, complex gearboxes, hydraulics, large bearings, large castings, or large blades;
- Low O&M due to simple, robust dynamic components.

Convenience of Deployment & Operation:

- Easy power capacity tailoring via modularity;
- High availability due to multiple small, low risk commodity wind turbines;
- User-friendly assembly, erection and servicing;
- Easy system deployment via system towing;
- Self-preserving anti-icing & lightning protection;
- Compliant structural & environmental characteristics.

Coverage Versatility:

- Economic offshore operation in virtually any depth water;
- High renewable energy recovery and on-demand (baseload) power supply capability per installation using combined windpower and fuel cells;
- Optional PV solar integration availability at reduced cost;
- Ability to make and store hydrogen fuel safely & operate integrally & economically with fuel cells.
- Pure water as by-product from wind powered electrolysis supplying hydrogen fuel to fuel cells.

The synergistic features of this internationally patented Spar-WARP™ technology, available under license, are poised to benefit global environmental goals as well as yield attractively low cost energy, plus provide excellent return on investment.

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