Advanced Performance Hydraulic Wind Energy

Jack A. Jones, Allan Bruce, and Adrienne S. Lam

***Abstract*—The Jet Propulsion Laboratory, California Institute of Technology, has developed a novel advanced hydraulic wind energy design, which has up to 23% performance improvement over conventional wind turbine and conventional hydraulic wind energy systems with 5 m/sec winds. It also has significant cost advantages with levelized costs equal to coal (after carbon tax rebate). The design is equally applicable to tidal energy systems and has passed preliminary laboratory proof-of-performance tests, as funded by the Department of Energy.**

***Index Terms*—wind, tide, energy, power, hydraulic**

I. Introduction

CONVENTIONAL wind turbines have low operating efficiencies, a mean-time-between-failure (MTBF) of only about one year, and large vibrational loads on the electronic generating systems on top of the wind tower. Direct Drive Train (DDT) systems and conventional hydraulic wind energy systems provide some improvements, as described below, but are not as efficient as a novel, improved hydraulic wind energy concept developed by the Jet Propulsion Laboratory, California Institute of Technology (JPL/Caltech).

A. *Conventional Wind Energy Systems*

Wind turbines have been used to generate electricity since the late 19th century, although the modern wind power industry did not begin until about 1979 when several European countries began commercially producing small wind turbines. Worldwide, wind power capacity is now ~430 TWh/yr, which is 2.5% of global electricity usage [1,2]. In the United States, offshore wind energy can potentially supply 4,000 TWh/yr and onshore wind energy an additional 37,000 TWh/yr [3]. The combined U.S. potential wind energy production is therefore about ten times the entire 2010 U.S. electricity demand of about 4,000 TWh/yr [4]. This is significantly more than all hydrokinetic energy combined (Table 1). Furthermore, wind energy costs are significantly lower than natural gas and solar power (Figure 1, [5]), or coal with carbon sequestration.

TABLE 1
HYDROKINETIC AND WIND ENERGY PRODUCTION POTENTIAL IN THE UNITED STATES

Type of Power	TW-Hr/Yr Potential in US
Ocean Waves	252
In-stream Tidal (Rivers, Tides, Gulfstream)	177
Offshore Wind	>4000
Onshore Wind	~37,000

The operating theory behind conventional wind turbines is shown schematically in Figure 2. Typically, three blades are used to harness the wind and transfer their slow-revolving torque to a gearbox. The gearbox increases the rotations per minute (RPM) to about 1800 RPM, and the attached alternator generates electricity. At high wind speeds, total efficiency is close to 80% of theoretical values, but this drops greatly at slower wind speeds. Not only does the total available power drop off according to the cube of velocity, but the relative efficiencies of the gearbox and alternator greatly decrease with wind speed. Due primarily to the gears and complex electrical equipment at the tower top, mean-time-between-failure (MTBF) is only about one year [6].

B. *Hydraulic Wind Energy Systems*

The gearbox is a primary point of failure mode for a conventional wind turbine, and servicing the generator and

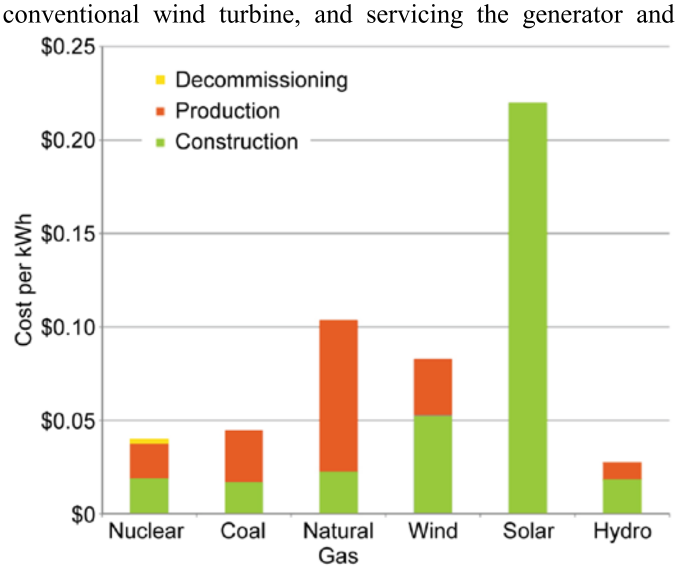

Fig. 1. Total Cost of Electricity Production per kW-hr

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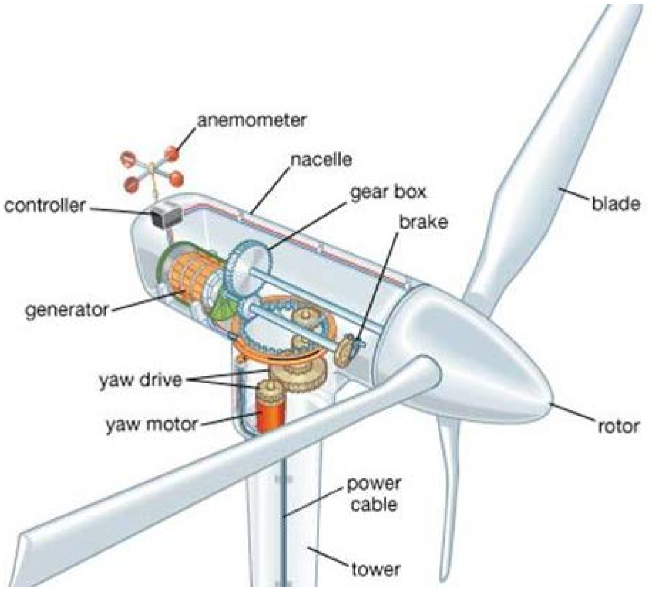

Fig. 2. Conventional Gear-Driven Wind Turbine

gearbox on the top of the wind mast is the primary maintenance cost. Three European companies (Chap Drive/Norway, Artemis/Scotland, and Voith Turbo WinDrive/Germany) have replaced the top-mounted wind turbine gears and generator with a top-mount hydraulic pump. The hydraulic pump then sends oil to a hydraulic generator at the bottom of the mast (Figure 3). The three big advantages to this type of conventional hydraulic wind transfer design are that the gearbox is completely removed, maintenance on the ground-level generator is greatly facilitated, and the mass on top of the tower is greatly reduced [7]. Unfortunately, each of these systems incorporates expensive, custom-made equipment, and the price has prevented this type of wind energy harvesting from expanding [8]. Also, each system has only one local generator at the bottom of the tower, thus losing a potentially very valuable means to increase efficiency, as will be described in a later section describing the JPL/Caltech Advanced Hydraulic Energy Transfer (HET) concept.

Delft University in the Netherlands has taken hydraulic wind power generation one step further for offshore wind power generation. They have designed a hydraulic oil loop on the mast to power a seawater pump that sends high-pressure seawater to a generator on a remote platform (Figure 4). Electricity from hydroelectric generators is then transferred to shore by means of a buried cable [7]. Total electromechanical efficiency is expected to be about 80%.

C. Direct Drive Train Wind Energy Design

A direct drive train (DDT) is one that takes the power coming from a motor without any reduction, such as a gearbox. This type of system has been used occasionally in offshore wind turbines, where the expense of repairing a gearbox is higher than the gearbox itself. Although DDT enables increased efficiency, reduced noise, and longer lifetime, it needs special, very expensive, and precisely controlled motors. Slow, high-torque motors are physically

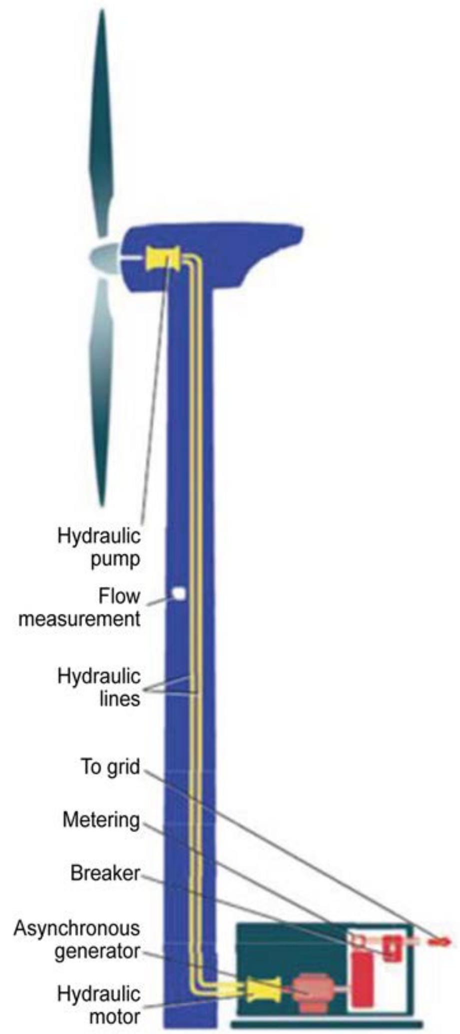

Fig. 3. Conventional Hydraulic Wind Turbine

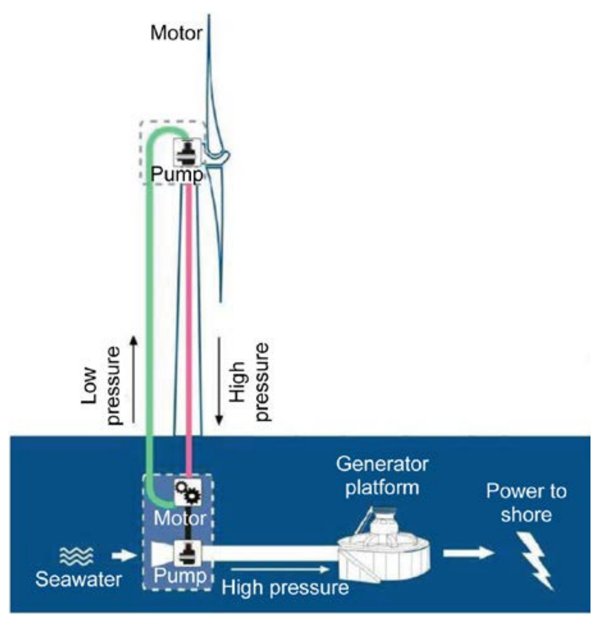

Fig. 4. Delft University Offshore Wind Hydraulic Concept

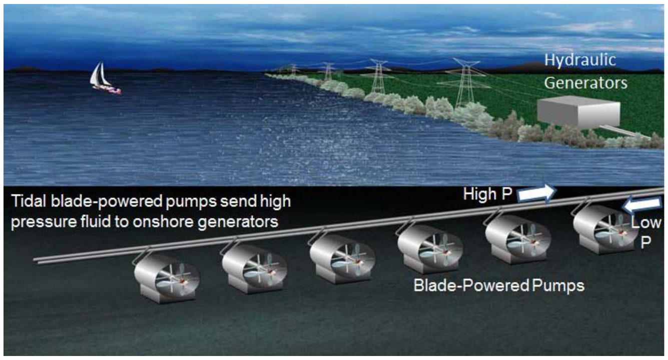

Fig. 5. JPL/Caltech Tidal Hydraulic Energy Concept

much larger than faster counterparts, and their mass needs to be supported at the top of the turbine tower. Low-voltage variations on high-speed motors with reduction to low RPM may be tolerable, but in direct-drive, such variations are directly reflected in the rotational speed. High efficiency DDT motors typically incorporate Neodymium (Nd) permanent magnets. Not only are these magnets very expensive, but 95% of Nd is currently supplied by China, where the vast majority of DDT deployments are found to date [9]. DDT systems can also use wound rotor generators, instead of permanent magnets. These generators are less expensive, but less efficient and far heavier.

II. ADVANCED HYDRAULIC WIND ENERGY DESIGN

A. Design Concept

JPL/Caltech improved the hydraulic wind energy concept significantly for both offshore and onshore applications. In this approach, a blade-driven pump is used to circulate environmentally friendly hydraulic fluid from a series of wind towers directly to a series of remote generators. For offshore systems these generators can be located onshore or on an offshore platform. This concept was originally designed for offshore tidal energy systems [10,11,12], as shown in Figure 5.

The basic tidal system was then reconfigured so that wind blades, instead of tidal blades could power multiple hydraulic pumps, which would then drive multiple, variable-displacement hydraulic generators, while keeping the RPM constant (Figure 6).

One major advantage is that the JPL/Caltech wind and tidal HET systems use scalable commercial-off-the-shelf (COTS) *radial piston pumps* (with typical efficiency ~0.95), to send a bio-friendly fluid to scalable *COTS, high efficiency, axial piston hydraulic generators* (Figure 7). As the wind speed decreases, the pressure drop decreases, *however*, the generator performance can be maintained at an optimal RPM by shutting off some of the generators (Patents granted and pending: [12,13]). In contrast, both the conventional and the European hydraulic systems suffer large losses as the RPM decreases. There are many efficiency advantages to using this novel HET technology which will be explained in greater detail below. For onshore wind generation, the pumps can connect to a

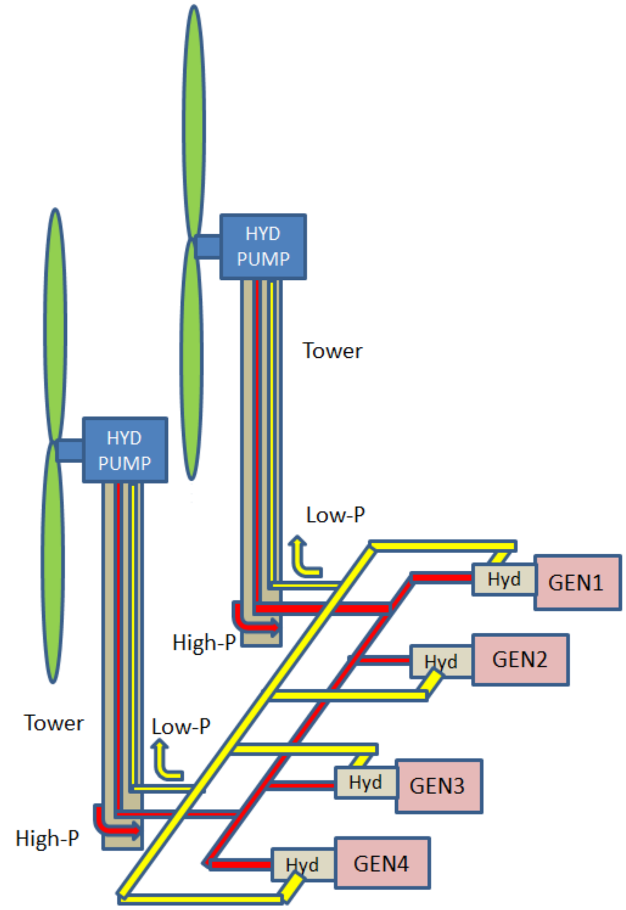

Fig. 6. JPL/Caltech Advanced Hydraulic Wind Concept

common high-pressure line that goes to a series of remotely located hydraulic generators. The returning low-pressure fluid then joins a common line to return to the blade pumps. This type of design not only eliminates all troublesome gears, it allows all ground-based generators to be at a common location. As the wind decreases, various hydraulic generators can be shut down to produce a nearly constant high RPM. Also, if there is a failure of one or more generators, they can easily be taken off-line (Figure 7). For offshore wind or for tidal energy, the oil cooling unit can be eliminated, since the pipes themselves will be cooled by the ocean.

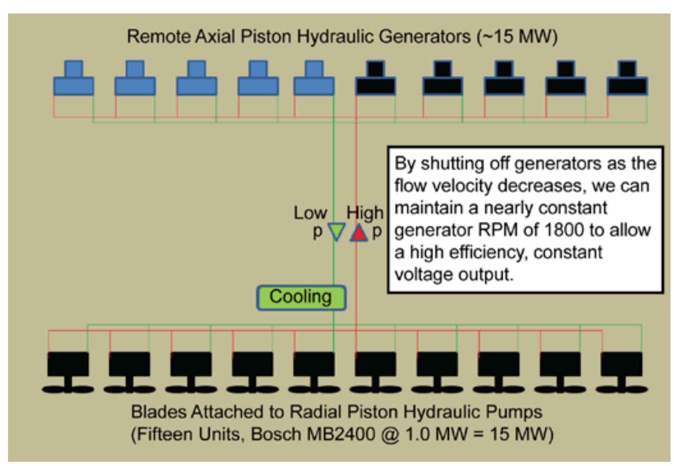

Fig. 7. Advanced Hydraulic Wind Energy Design

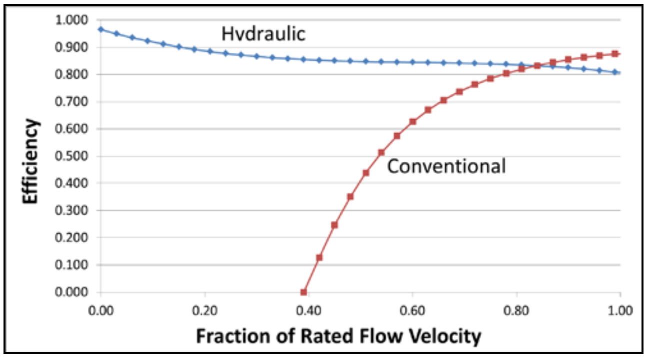

Fig. 8. Advanced Hydraulic Efficiencies Compared to Conventional Generator * Gear * Power Conditioning Efficiency

The novel combination of wind energy and HET, based on COTS components, enables a high-efficiency, low-cost, environmentally-safe, wind power solution for on-shore and off-shore deployment.

B. Performance of Advanced Hydraulic Wind Energy

Preliminary sizing has been conducted as part of an on-going DOE funded project, led by Sunlight Photonics. For onshore and offshore wind, a small 15-MW COTS system has been sized. This can be scaled to larger power systems. We have selected a 1 MW, 60-m diameter blade sets that rotate at about 20 RPM, for maximum wind velocity of 12 m/sec (27 MPH). Each set of blades is connected to a Hagglunds radial piston pump (#MB2400-1950).

For this particular example, we assume the generators are located 500 meters away from the wind pump units. The average inner diameter (ID) of the high-pressure (3000 psi or 207 bar) stainless steel pipe is 35 cm and the average ID of the low-pressure (150 psi or 10.3 bar) reinforced fiberglass pipe (RFP) is 40 cm. The costs of pipes and fluid are relatively low compared to the total Levelized Cost of Energy (LCOE) [15]. The total pressure drop is 5% of the entire flow for the 500-m × 2 roundtrip length. Distances longer than 500 meters would require larger diameters in order to maintain the same 5% total pressure drop. The total efficiency of the wind or tidal HET system for full rated flow velocity is:

Hydraulic Efficiency = Pump Effic*Pressure Effic*Hydraulic Motor Effic *Generator Effic
= ~ 0.95 * 0.95 * 0.95 * 0.95 = ~ **0.81**

At 1/3 of the full rated flow speed, the hydraulic pump efficiency increases to about 0.963 (Figure 9) and the pressure drop efficiency increases to at least 0.99. The hydraulic motor and generator efficiency both stay at 0.95 by means of shutting off generators. Thus, total efficiency ***increases*** to about 0.860 (Figure 8). It should be noted that the efficiency curves of the MB2400-1950 for wind turbines are shifted for the somewhat higher RPMs and lower torques corresponding to wind turbines (Figure 9). This is a large improvement over other

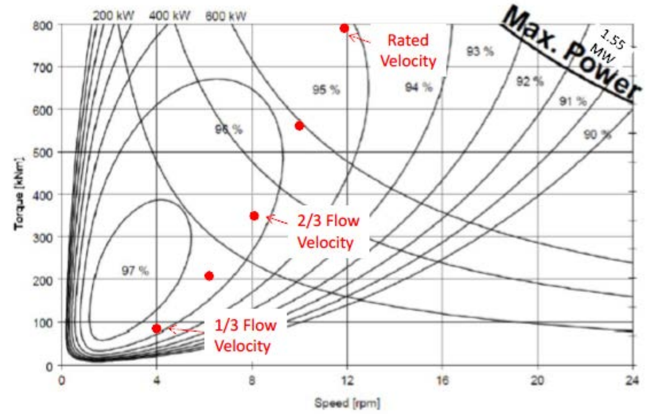

Fig. 9. Efficiency Curves for MB 2400 Hydraulic Pump with 1 MW rating. Red Points Refer to Reduced Wind Velocities

wind turbine systems, which suffer significantly ***lower*** efficiency at low wind speeds (Figure 8). Conventional wind turbine combined gear/electronic efficiencies [14], excluding power conditioning, vary from about 0.87 (full rated wind velocity), to about 0.7 at 0.7 rated velocity, and to zero (0.4 rated velocity).

The general shape of the "Hydraulic" curve in Figure 8 has, in fact, been proven in a recent Hydraulic Tidal Energy project Task [15], which has significant similarity to hydraulic wind energy. For this task, a laboratory system was designed, constructed, and tested (Figure 10). It simulates a tidal energy turbine, with a 2-m diameter blade in up to a 2.9 m/sec flow. The system consists of a drive motor assembly providing appropriate torque and RPM, attached to a radial piston pump. The pump circulates pressurized, environmentally-friendly, Hydraulic Environmental Ester Synthetic (HEES) hydraulic fluid in a closed loop to an axial piston motor which drives an

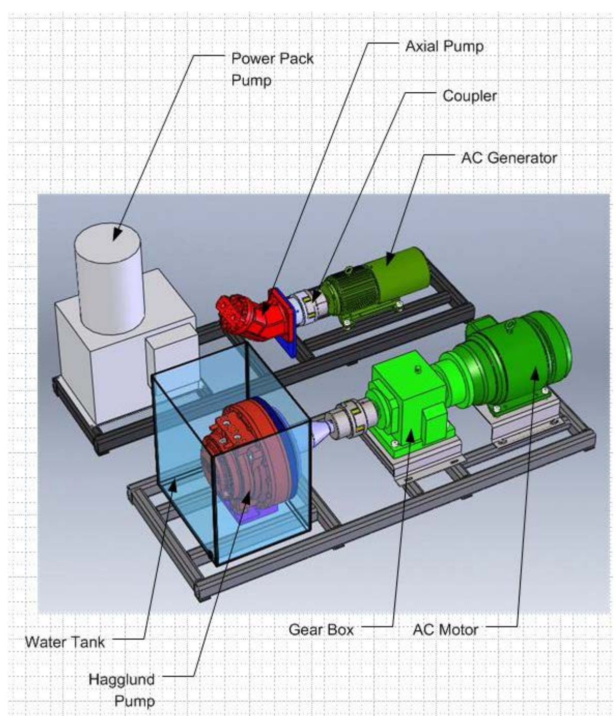

Fig. 10. Hydraulic Energy Test Setup

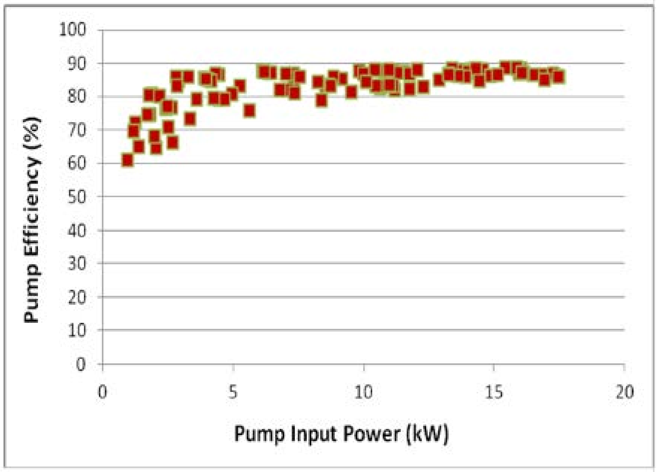

Fig. 11. Measured Pump Efficiency in a 1–3 m/s Simulated Tidal Flow

electrical generator, with a resistive load. The performance of the components, subsystems and full system were evaluated during simulated tidal cycles. The COTS pump and motor were selected to scale to MW size and were greatly oversized for the laboratory demonstration. Hydraulic pump efficiencies of 90% have been confirmed in simulated tidal flows between 1 and 3 m/sec at only 1–6% of rated power (Figure 11). These efficiencies are 95–96% at higher operating powers.

The overall C_p, or fraction of total wind power passing through the blades to the gearbox, is shown in Figure 12 for a typical variable blade angle of attack wind energy system [14].

The total efficiency for conventional and advanced hydraulic wind turbines is then represented by C_p times the efficiencies from Figure 8. For a typical Weibull wind distributions [16] shown in Figure 13, the ratio of total power produced by advanced HET compared to conventional wind turbines varies as per the mean wind velocity, as shown in Figure 14 and tabularized in Table 2. A rated wind speed of 11 m/sec is assumed for all points, unless a higher rated wind speed allows for more optimal wind energy production.

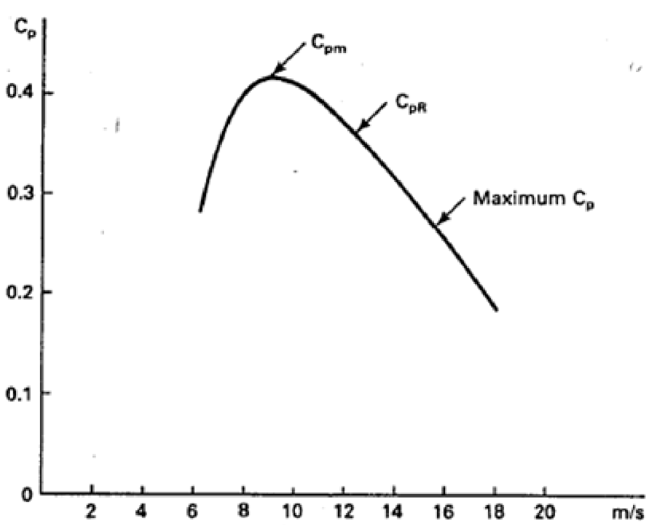

Fig. 12. Typical C_p for Conventional Wind Turbine with Variable Pitch (Rated Speed = 12.3 m/sec)

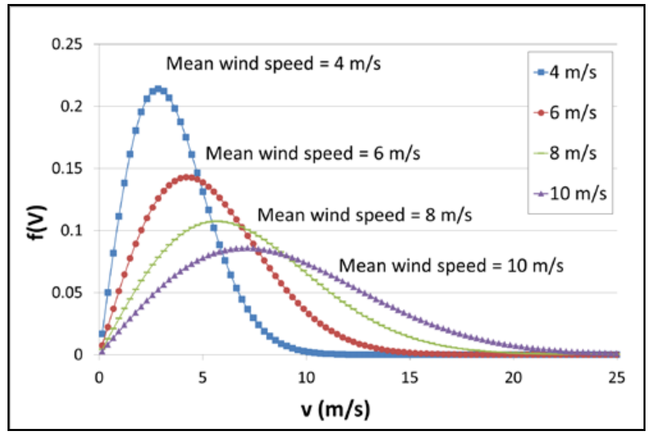

Fig. 13. Typical Weibull Wind Distributions

For more common wind speeds of 5–7 m/sec (Figure 15), the advanced HET system has performance improvements of about 8%–28% over conventional wind turbines, assuming a rated wind speed of 11 m/sec or larger. The carbon footprint and environmental impacts will largely mirror those of current COTS wind turbine systems and towers. The preferred hydraulic fluid is HEPG (polyethylene glycol), a non-toxic, environmentally friendly, biodegradable oil which is used as a food additive and is fully miscible with water. Testing has shown HEPG has no adverse effects on organisms even at levels of 1% [18].

The maximum unit size for this type of Hydraulic Wind

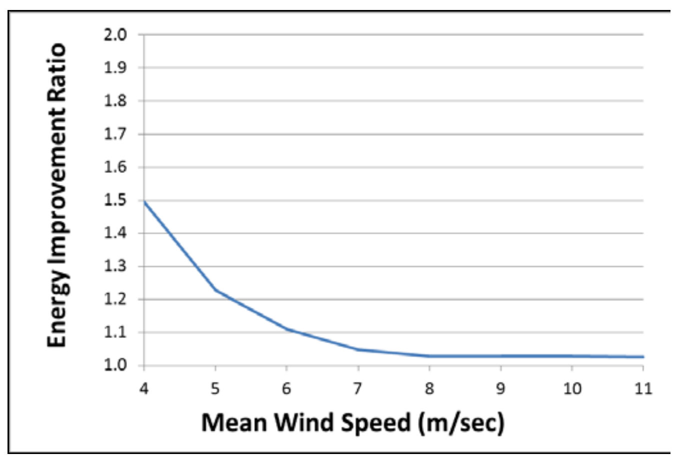

Fig. 14. Ratio of Advanced HET Energy to Conventional Wind Turbine Energy for Various Mean Wind Speeds

Mean Wind Speed (m/s)	Energy Ratio	Optimal Rated Speed (m/s)	
		Conventional	HET System
4	1.496	11	11
5	1.227	11	11
6	1.109	11	11
7	1.048	11	11
8	1.027	11	12
9	1.028	13	14
10	1.026	14	15
11	1.024	15	17

TABLE 2. TABULAR VALUES FOR FIGURE 14

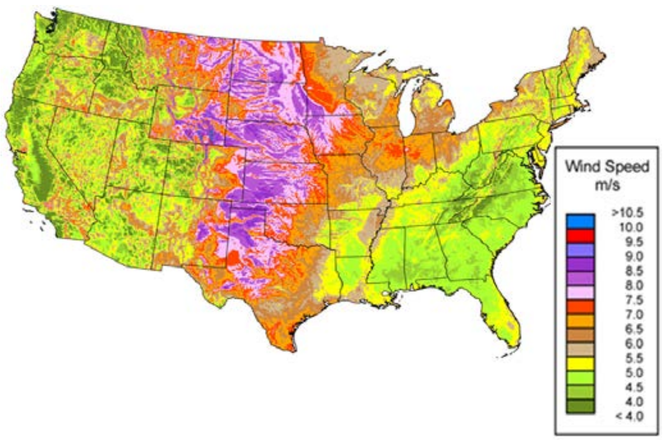

Fig. 15. Mean Wind Speeds over Continental United States [17]

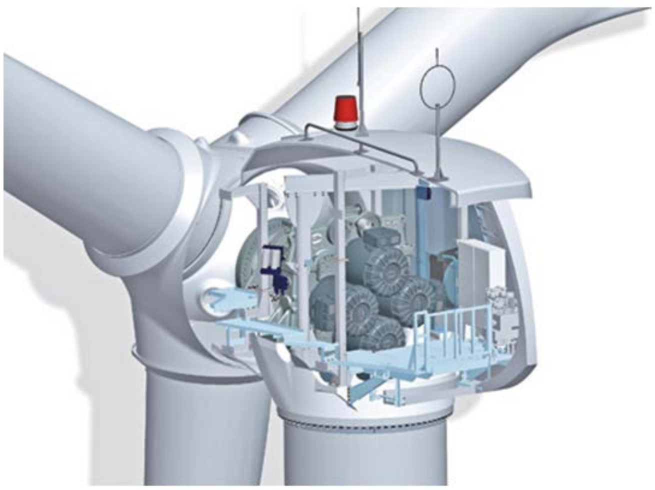

Fig. 16. Torque Splitting Between Four Electrical Generators on the 2.5 MW Clipper Liberty

Energy Transfer system is about 1.5 MW per tower, limited by available COTS hydraulic pumps. One means of obtaining up to 6 MW of energy or more per tower is to split the blade torque energy between four different generator systems, as is done with the 2.5 MW Clipper Liberty wind turbine (Figure 16). Although this involves a single gear that splits energy to four other geared generators (or pumps), it can be designed without gear reduction, and thus stress and energy losses are minimized.

There is no effective limit for the ***total*** power which can be produced using multiple wind towers; any number of 1 MW COTS hydraulic motors and generators can be used. If such long-lived, low-cost wind energy systems become prevalent, it is likely that pumps larger than 1.5 MW will be produced to handle larger wind energy outputs.

The Levelized cost of energy (LCOE) for conventional wind energy is about \$0.097-\$0.022 (tax rebate) = \$0.075/kW-hr [29]. Additional costs for conversion to advanced hydraulic (pumps, pipes, fluid, and hydraulic generators) are approximately \$0.020/kW-hr [15, 30]. Maintenance costs [29] are expected to be reduced from about \$0.010/kW-hr to 0.004/kW-hr (savings of \$0.006/kW-hr). Due to the reduction of costs by eliminating gears [31] and reduced costs of a lighter tower, hub, shaft, and main frame, as well as lower costs of power conversion (constant RPM), an additional cost reduction of about \$0.035 is expected. Approximately 12% improved capacity factor for most U.S. populated areas (East Coast and West Coast) with wind speeds of 5-7 m/sec (Fig. 14 and 15) results in additional cost savings of about \$0.097*0.12 = \$0.0116/kW-hr. Thus,

<u>Advanced Hydraulic LCOE</u> = 0.097 - 0.0116 (efficiency) – 0.006 (maintenance) - 0.035 (reduced capital equip) + 0.020 (hydraulic conversion) – 0.022 (tax rebate) = \$0.0424/kW-hr

Thus, a first approximation of LCOE for advanced hydraulic wind energy (with tax rebate) is approximately equal to that of coal (Fig 1).

III. Conclusions

The JPL/Caltech advanced hydraulic energy transfer system for wind energy has the potential to greatly improve the reliability, performance, and thereby the costs of producing wind energy for typical mean wind speeds of 5–7 m/sec. In this wind regime, we can expect up to 23% performance improvement compared to alternative wind energy systems. Also, there is a significant cost reduction in the towers (less supported mass), lower power conditioning costs (fixed RPM generators), and low maintenance costs (no gears and power generation moved to central ground location). This new approach combines the best advantages of conventional, hydraulic, and DDT wind energy systems.

Total levelized cost of energy is expected to be approximately \$0.0424 kW-hr (with tax rebate) for most wind areas near major populated US regions. This is equivalent to energy costs with coal, and it is less than energy costs from natural gas, but without any carbon footprint.

Acknowledgment

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