Evaluation of Small Modular Wind Energy Conversion System

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Keywords: Case Study, Energy economics, Financial Study, Wind Amplified Rotor Platform, Wind Power.

Abstract: A probabilistic method based on the Weibull distribution for predicting the economic performance and reliability of small autonomous wind energy conversion (WEC) systems is described. These systems contain WARP (Wind Amplified Rotor Platform), an adaptable design of wind generator, along with the WARP-GT (generation-transmission) system which combines both electricity generation through wind energy conversion and electric power transmission. Furthermore, this work explores the use of pumped-storage, aiming to firm up the intermittent nature of the system. Results of this prediction are applied in the cost estimation of an investment from the private owner view. The cost estimation is based on a power law ratio for industrial equipment. Results are presented for two case studies located in Greek islands.

1 INTRODUCTION

Wind energy use has several attractive features. Typically, high wind regimes occur in areas with low priority land use classification. The energy in the wind can be easily converted to rotary mechanical energy by aero turbines and to electrical energy by coupling generators. The collection area is perpendicular to the ground with surface area equal to the area swept by the blades.

Since the power density in moving air (wind) varies as the cube of the wind speed, the power output of a wind energy system will have wide variation similar to the variations in the wind speed. Therefore, to provide a reliable supply (electrical, mechanical, or thermal) to consumers, one has to employ some type of energy storage and reconversion system to smooth out the variations and supply energy during calm periods. An alternative approach is to have a conventional backup system of sufficient capacity, which by itself could supply the consumers if necessary.

As a result of the increasing interest in the use of wind energy systems the European Union has given a series of incentives to individuals and companies in member countries to install privately owned wind arrays. The partial subsidy of the initial investment cost by the EU along with the provisions for sales of the excess wind generation back to the electric utilities has made investing in wind generation profitable in places with high average wind velocities (>4.5 m/s) (Tigas et al., 2015). The Greek islands appear prosperous for investment since they are in an area of Europe with high mean wind speeds (>7.5 m/s).

The objective of this study is to undertake a three-step assignment to investigate applications of a Wind Amplified Rotor Platform (WARP) (Weisbrich et al., 1995), and the feasibility of employing wind power for the Greek islands as a possible energy source and fuel saved, using probabilistic methods. The method of cost analysis employs a power law applied to plant-capacity for fixed cost. The probable accuracy of estimation is perhaps ± 30%, which is adequate for a preliminary feasibility study.

Finally, this work explores the use of "pumped-storage", to firm up the intermittent nature of wind-generated power. Pumped-storage is defined as the use of hydroelectric or thermal power to pump water into a reservoir during periods of low demand and to let it out during periods of high demand. This involves the use of a turbine/pump, which can either pump water up, or have water released through it to produce power. The operation is considered worthwhile, because the pumping energy can be purchased at low cost, while the produced peaking power has a high value. Using a wind turbine in

Ioakimidis, C., Galatoulas, F. and Porter, R.
Evaluation of Small Modular Wind Energy Conversion System.
DOI: 10.5220/0006774502780285
In *Proceedings of the 7th International Conference on Smart Cities and Green ICT Systems (SMARTGREENS 2018)*, pages 278-285
ISBN: 978-989-758-292-9
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conjunction with pumped storage would involve using the irregular wind power penetration to pump water to a reservoir, from which it would be released to generate power as needed. This would make possible to turn intermittent, unreliable power into firm power, at a cost in efficiency.

2 NOMENCLATURE

v	Velocity (m/s)
K_h	Shape parameter at height h
C_h	Scale parameter at height h (m/s)
α_h	Wind shear exponent at the reference height (dimensionless)
ICC	Initial capital cost (€)
$A_{O\&M}$	Annual operation and maintenance cost (€)
COE	Cost of energy (€/kWh)
A	Annual Investment Cost (€)
$\overline{E}$	Expected average power (kW)
E_W	Annual energy production (kWh)
$E_{W,I}$	Annual energy production (kWh) by i^{th}-WARP

3 WIND ENERGY ANALYSIS

WARP and its variant for generation and transmission (WARP-GT) have been analyzed and studied in a large scale system before by (Weisbrich et al., 1995) and compared with the large model designs of MOD-1, MOD-2, MOD-5A, WTS-4, and Aeolus. The modular WARP contains a tower which the turbine generators are mounted on at various heights, as illustrated in Figure 1. The greater the height, the greater the wind and power output per generator. Turbine generators can vary from 20 to 70 kW. We chose a 25-kW generator model in case A, and a 30-kW generator model in case B. The resulting cost for a 50-module 4.5 MW unit is €850 / kW. In the island of Krete (case A) we will consider 3 identical units with 3 modules in the same tower, each one at different heights, namely 11.2 m, 15.8 m, and 20.4 m, adjusted at three different wind speeds having a total capacity of 450 kW. In the island of Syros (case B) we will consider 11 identical towers, each one of 300 kW capacity, consisting of 5 modules at different heights and a total capacity of 3,300 kW.

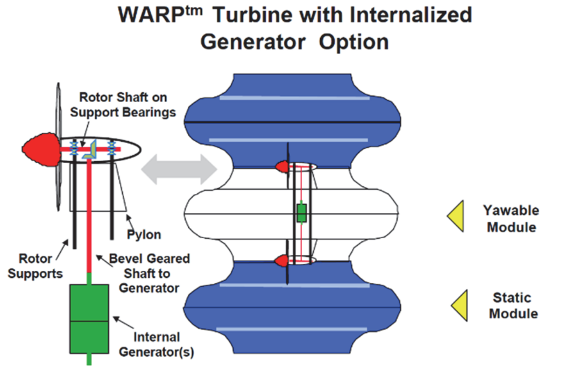

Figure 1: WARP Turbine module and rotator layout [retrieved from (Weisbrich et al., 1999)].

Unlike other wind energy conversion (WEC) systems, WARP has the following characteristics:

- Lower cut-in velocity at which time power is generated by the turbines and directed to the utility grid (assumed here $v_{ci} = 0$).
- The power output is a function of the height of the tower.
- The upper cut-out velocity for each of the turbines at the different heights is the same, i.e. $v_{co} = 22.2$ m/s.

At any particular fixed reference height, the wind speed and direction is not constant but can fluctuate greatly. In our case, we have average mean wind speeds for a period of 10 years. The mean velocities are generally counted and tabulated so that a velocity frequency curve can be drawn. Actual field measurements of wind velocity can be mathematically approximated by several probability density functions, most notably by the Weibull and Rayleigh distributions.

The Rayleigh distribution long-time mean wind speed is given by the following equation:

$$P(v) = \frac{v\pi}{2\overline{v}^2} e^{\frac{-v^2\pi}{4\overline{v}^2}} \quad (1)$$

where v is the windspeed, P(v) is the probability or percent time wind is of velocity v, and $\overline{v}$ is the long term mean windspeed.

Although Rayleigh distribution incorporates mean wind velocity, it is only a one-parameter distribution, which according to many statisticians is inadequate to describe precisely a wind speed distribution for wind power studies.

Nowadays one of the most useful distributions for wind power studies is the Weibull distribution. The standard deviation σ is given below:

$$\sigma = \{\Gamma(2/K+1) - [\Gamma(1/K+1)]^2\}^{1/2} \quad (2)$$

where Γ is the Gamma function and for various values of K between the range 1.2 - 6.0 the standard deviation has the values from 0.7872 - 0.1850. The authors in (Simiu et al., 1996) suggest that if K = 2 the Weibull distribution reduces to Rayleigh distribution. For higher values of K, as we have in our cases, there is a decrease in the standard deviation that gives better results in our prediction of the wind characteristics. The study in (Ramler et al., 1979) shows that there is an empirical relation between the mean wind speed and the shape parameter for standard deviation, $0.3 \leq \sigma \leq 0.7$, that can describe the shape parameter K. According to these studies, we know that the Weibull distribution in its general form is appropriate to estimate wind characteristics and is given by the formula:

$$P(v) = \frac{K\left[\Gamma\left(1+\frac{1}{K}\right)\right]^K v^{K-1}}{\bar{v}^K} e^{-\left[\Gamma\left(1+\frac{1}{K}\right)\frac{v}{\bar{v}}\right]^K} \quad (3)$$

where

$$K \approx 1.09 + 0.2\,\bar{v}$$

$$C = \frac{\bar{v}}{\Gamma\left(\frac{1}{1+K}\right)} \quad (4)$$

Wind speeds at elevations other than the reference elevation are given as follows:

$$v = v_r\left(\frac{h}{h_r}\right)^{\alpha} \quad (5)$$

where v is the velocity at height h, v_r is the velocity at reference height h_r , α is the wind shear exponent that equals α_0 (1-(log v_r/log v_0)), with α_0 = (Z_0 / h_r), Z_0 = surface roughness length (0.2 m), and v_0 = 67.1 m/s.

The mean value from the annual windspeed distribution for the reference elevation of 10 m is 8.25 m/s for the island of Krete and 7.5 m/s for the island of Syros. At other elevations, the wind gradient power law is used to modify the Weibull parameters as follows:

$$K_h = \frac{K_r}{\left[1-\alpha_0\left(\frac{\log h/h_r}{\log v_0}\right)\right]} \text{ (dimensionless)} \quad (6)$$

$$C_h = C_r\left(\frac{h}{h_r}\right)^{\alpha_h} \text{ in m/s} \quad (7)$$

where,

$$\alpha_h = \alpha_0\left(1-\left(\frac{\log v_r}{\log v_0}\right)\right) \text{ (dimensionless).} \quad (8)$$

A variable that effects turbine performance is the change in air density, which depends on pressure and temperature through elevation and weather. Elevation ranges from 11.2-20.4 m for case A, and from 11.2-29.5 m for case B. The effect of pressure and temperature can be described with the equation of state for ideal gases:

$$\rho = P / RT \quad (9)$$

where P is the absolute barometric pressure, ρ is the mass density, R is the gas constant, and T is the absolute temperature.

Since R is constant, two states can be linked in the following relation

$$P/\rho T = P_0/\rho_0 T_0 \quad (10)$$

where subscript $_0$ denotes sea level standard condition. Thus

$$\rho_0 / \rho = (P / P_0)(T_0 / T). \quad (11)$$

With T_0 = 298 ° K, we assume T = 300° K for the examined period. From Atmospheric Standards, the ratio P / P_0 for the above heights has no significant change. Thus we assume that air density is constant at a value of $\rho = 1.225$ kg/m^3.

From the specific windspeed duration curves, computing the output power at that particular windspeed and integrating over the appropriate time duration will yield the annual energy output:

$$\bar{E} = \int_0^{\infty} E(v)P(v)dv = \int_0^{22.2} E(v)P(v)dv \quad (12)$$

where the total available wind power is:

$$E = \frac{1}{2}\rho v^3 A \quad (13)$$

Since the wind turbine only produces power when the wind speed is between cut-in (= 0 for WARP) and the cut-out wind speed, the integration of Equation (13) needs to be performed only over these limits.Results of this analysis with the characteristics of the rotors for each unit in the two cases are given in Tables 1 and 2.

Figures 2-3 illustrate the comparison of the output power using Weibull vs Rayleigh distribution for the two islands. It is readily apparent that Rayleigh distribution is much more conservative and has generally lower probability of velocity curves than using the two parameter Weibull distribution.

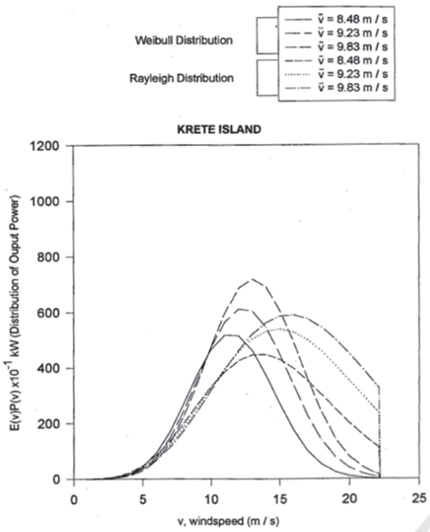

Figure 2: Output Power Comparison for the Island of Krete Using Weibull-Rayleigh Distribution (Case A, Total Load Demand 12,503 MWh).

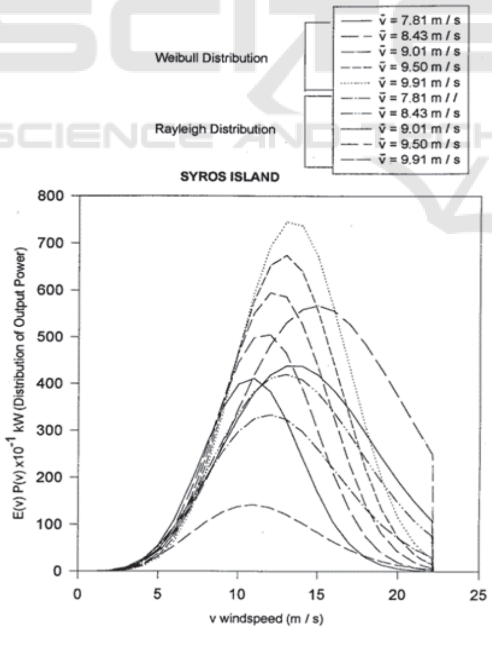

Figure 3: Output Power Comparison for the Island of Syros Using Weibull-Rayleigh Distribution (Case B, Total Load Demand 53,908 MWh).

3.1 Pumped Storage Sizing

A suitable site for a wind-powered pumped-storage facility requires wind, a reasonable storage facility, and head, in addition to water (Figure 4). The site concentrating the above elements identified in this paper, is the island of Krete. To simulate pumped-storage production, hourly, daily or yearly average windspeed was needed (Caralis et al., 2012). Again, it was selected according to the yearly average wind speed of 8.25 m/s at the elevation of 10 m.

Table 1: Wind-Site Unit Performance/Turbine Characteristics-Wind Speed Distribution-8.25 m/s mean windspeed-Shear = 0.247, Density = 1.225 kg/m3, vco = 22.2 m/s, 3 modules of 2 turbines each.

Hub-Height (m)	Module #	kW per turbine	kWh/turbine per year	Total kWh/turbine per year
11.2	1	25	33,000	66,000
15.8	2	25	43,000	86,000
20.4	3	25	52,000	104,000
			Total:	256,000

Table 2: Wind-Site Performance/Turbine Characteristics - Wind Speed Distribution - 7.5 m/s mean windspeed - Shear = 0.258, Density = 1.225 kg/m3, vco = 22.2 m/s, 5 modules of 2 turbines each.

Hub-Height (m)	Module #	kW per turbine	kWh/turbine per year	Total kWh/turbine per year
11.2	1	30	26,600	53,200
15.8	2	30	34,500	69,000
20.4	3	30	42,500	85,000
25	4	30	49,600	99,200
29.5	5	30	56,300	112,600
			Total:	419,000

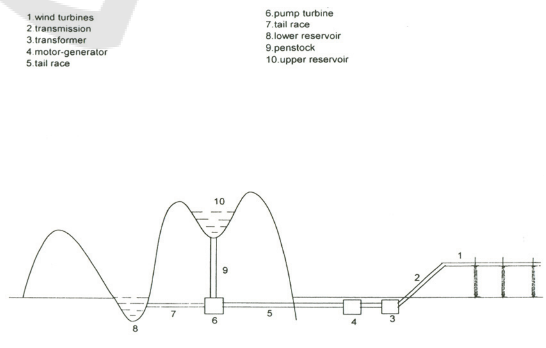

Figure 4: Modular Wind-Powered Pumped-storage system design.

Next, one uses the power produced by the turbines to pump water into the pumped-storage reservoir. This involves converting the hourly power input into the volume of water lifted into the

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reservoir each day of each month in the time period (Ter-Gazarian, 1994). The output is volume of water lifted 300 meters in one second with 100% efficiency. In this case, an efficiency factor of 80% was selected for the use of windmills pumping water into the pumped-storage reservoir. Thus the volume of water lifted in 300 meters per day by the 256,000 kWh wind turbine installation is V = 72.6 m^3.

At a head of 300 meters, 1,571 m^3 would generate 1,000 kWh, or 1 MWh. The release of 72.6 m^3 would then generate 0.0462MWh per day or 16,876 kWh. If the average home uses 15,500 kWh per year, then this pumped storage facility could handle the needs of about 1 household, with one windmill, once it was filled. For a small n, say n = 50, n windmills could handle the needs of 50 homes or a peak load demand of (15,500)(50) / (3,600) = 208 kW which is the peak load demand of a medium size village on a Greek island.

4 METHOD OF ECONOMIC ANALYSIS

In this study, the power system is assumed sufficiently large compared to the wind penetration, so that there is no restriction to the power produced by the wind generation.

In case A, the wind turbines are connected to the local distribution network, while in case B the wind farm is scheduled by the utilities to be connected to the power system. Cost of capacity is taken to be dependent on a power x of capacity. The power x has been found by (Peters et al., 1968) to vary between 0.6-0.8 for many process facilities. In this case, we take it as 0.8 which reflects the economy of scale generally encountered in recent history.

The work in (Weisbrich et al., 1995) gives results of a 50 MW wind power production for WARP-GT and WARP for two different cases of mean windspeeds of 5.8 and 8.0 m/s respectively. The total initial capital cost includes the turbine system cost and balance of station as well as the land area of the windmills. For WARP-GT with 5.8 m/s mean windspeed and 20 units each of 2.5 MW capacity and 50 module per unit, the total initial capital cost for 45 MW is €36,394,000, while for 8.0 m/s mean windspeed and the same number of module per unit, but now for 8 units each 6.2 MW totalling 49.6 MW, the total initial capital cost is €17,415,300. For the first mean windspeed mentioned, for 151 units, each of 330 kW, and 11 modules, totalling 49.83 MW, the total initial capital cost is €30,894,700. For 8 m/s mean windspeed with the same number of modules on each of the 56 units, each unit of 900 kW capacity, totalling 50.4 MW, total initial capital cost is €18,217,000.

There is a correlation for the 11 modules per unit between mean wind speeds and initial capital cost. Since this correlation is not linear, we will use a power correlation given by the formula

$$\ln y = \ln b + m \ln x \qquad (14)$$

where y is initial cost and x is windspeed.

If we try to find the values of m and ln b these are: m=-2.2922 and ln b=21.5562. Thus the power correlation becomes:

$$\ln y = 21.5562 - 2.2927 \ln x \qquad (15)$$

for x=8.0 m/s mean windspeed.

Using this correlation, we first extrapolate for v=8.25 m/s mean windspeed for the average capacity of 50.115 MW and we find an initial capital cost of €17,275,700.

We repeat the process but now for 50 modules per unit. The power correlation between the mean wind speeds and the total initial capital costs for v=8.25 m/s with the average capacity of 47.3 MW, results in a €16,207,100 total initial capital cost.

5 RESULTS

5.1 Case A: WARP-GT Krete

For the WARP-GT on the island of Krete, there are two values that result by using the power correlation and subsequently the power ratio law.

- $€16,207,100 = a\ 47,300^{0.8} \Rightarrow$
  $a = €2,950 / kW^{0.8}$ with 50 modules per unit, and
- $€17,275,700 = a\ 50,115^{0.8} \Rightarrow$
  $a = €3,000 / kW^{0.8}$ with 11 modules per unit.

Since the examples that will be used in this study are for a small-scale system, we assumed that our study is closer to the one by (Weisbrich et al., 1995) of 11 modules per unit. As can be seen from the results above, there is not a large difference cost per kW using the 50 modules per unit or the 11 module per unit case. For a 450 kW capacity the initial capital cost is:

$$ICC = €(3,000)\ (450)^{0.8} = €400,000 \qquad (16)$$

We now express cost in terms of a power law ICC = b $N^{0.8}$ and a module power law ICC = c $N^{0.8}$.

For the first of the three units using the power factor, the initial capital cost is:

$$b = €400{,}000 / 3^{0.8} = €165{,}000 \quad (17)$$

In addition the cost of the first module per unit, since each unit contains 11 modules is:

$$c = €165{,}000 / 11^{0.8} = €24{,}000 \quad (18)$$

The annualized operation and maintenance cost is taken as 0.5% of the initial capital cost. For a 450 kW capacity:

$$A_{O\&M} = (0.005)\,(€400{,}000) = €1{,}990 \quad (19)$$

The WARP's initial capital cost is annualized in real currency by multiplying it with the following annualization factor:

$$\alpha = \frac{\tau}{1-(1+\tau)^{-n}}\,,\ \tau = \frac{1+i}{1+u} - 1 \quad (20)$$

where n is the expected wind generator service time, i is the market interest rate, u is the inflation rate and τ is the real interest rate. In this case n = 15 years, i = 12%, u = 5.7 %, results in $\alpha = 0.135$. So the annualized investment cost is:

$$A = (0.135)\,(€400{,}000) = €54{,}000 \quad (21)$$

The total wind park production (in kWh) is:

$$E_W = \sum_{i=1}^{N_w} E_{w,i} = \sum_{1}^{3} E_{w,i} = (256{,}000)(3) = 768{,}000 \quad (22)$$

The cost of energy is thus:

$$COE = \frac{A_{O\&M} + A}{\bar{E}} = \frac{54{,}000 + 1{,}990}{(256{,}000)(3)} = €0.072 / kWh \quad (23)$$

The mean power or (utilization factor) as percentage of the installed power is: 768,000 / (450)(8,760) = 19.5 % or 0.195.

The Benefit Cost Ratio (B/C) in WARP-GT, which allows us to see if an investment is profitable or not is given by the formula:

$$B/C_{ratio} = \frac{\text{Revenues from Wind Sales to the PPC per year}}{\text{Annualized Cost + Maintenanc eCost}} \quad (24)$$

The revenues from wind sales to the utility company, which in this case is the Public Power Corporation (PPC) are computed for each day as follows:

$$\text{Revenues of wind sales per day} = C_T \quad (25)$$

where C_T (€/kWh) is the cost rate of the wind energy sold to the PPC. In this context, the purchase and sales rates from the Producer Price Indices were €0.09945/kWh and €0,172/kWh respectively (Eurostat, 2017). So continuing our economic analysis we have:

$$B/C_{ratio} = \frac{(0.09945)(256{,}282)(3)}{56{,}000} = 1.3 > 1 \quad (26)$$

Since $B/C_{ratio} > 1$, this means that the installation of these three identical units is a profitable investment. The revenues in the period of the 15 years will be given by the formula:

$$A_{rev} = \frac{\text{Revenues of Wind Sales to PPC}}{\text{Annualized Factor}} \quad (27)$$

As an alternate economic evaluator, the simple payback period (SPP) of our investment is the period that we will gain profits from the wind sales to the PPC. SPP with 100% availability is given by:

$$SPP = \frac{ICC}{A_{rev} - A_{O\&M}} = \frac{400{,}000}{(0.0994)(256{,}000)(3) - (1{,}990)} = 5.3\,Years \quad (28)$$

Table 3: WARP System and COE for the Island of Krete - 450 kW Wind Power Production - 8.25 m/s mean windspeed - 3 module.

No. of Units	3
kW / Unit	150
Total ICC (Initial Capital Cost)	€400,000
Cost per kW	€3,000
Cost per Unit	€165,000
Cost per Module	€24,000
$A_{O\&M}$ Cost	€1,990
Annual Energy Production (net)	770,000 kWh / yr
Cost-of Energy	€0.072/kWh
B/C_{ratio}	1.3>1 (profitable)
A_{rev}	€565,000
SPP	5.3 years

5.1.1 Pumped Storage

For a 7.5 MW capacity the initial capital cost is:

$$ICC = €(3{,}000)(7{,}500)^{0.8} = €3{,}800{,}000 \quad (29)$$

The annualized operation and maintenance cost is the 0.5% of the initial capital cost. For a 7,500 kW capacity:

$$A_{O\&M} = (0.005)(3{,}800{,}000) = €19{,}000 \quad (30)$$

The WARP's initial capital cost is annualized by multiplying it with the following annualization factor as in Eq. (21). In this case n = 20 years, i = 12%, u = 5.7%, results in $\alpha = 0.085$. Therefore, the annualized investment cost is for n = 50:

$$A = €\,(3{,}800{,}000)(0.085) = €320{,}000 \quad (31)$$

The cost of energy is thus:

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$$COE_{(1)} = \frac{A_{O\&M} + A}{\bar{E}} = \frac{320{,}000 + 19{,}000}{(256{,}000)\ (50)} = €0.026/kWh \quad (32)$$

In the case of the system of Krete, for the pumped storage facility we need total generation of 92.6 kW/year.

A lower value for the cost of a pumped storage generating facility might be obtained by considering an 8 MW unit, which, including a spherical valve, motor-generator, governor, and shipping and handling, would cost on the order of €1,160,000, without concrete, (Loewus et al., 1984).

Hence we have:

$$\text{Cost of eq. a} = \text{Cost of eq. b}\left(\frac{\text{Cap.of eq.a}}{\text{Cap.of eq.b}}\right)^{0.86} \quad (33)$$

resulting in €55,000 for the specific investment. In this case n = 50 years, i = 12%, u = 5.7%, results in $\alpha = 0.0625$. So the annualized investment cost is:

$$A_{O\&M} = (55{,}000)\ (0.0625) = €3{,}400 \quad (34)$$

he cost of energy for the pumped-storage system is:

$$COE_{(2)} = \frac{3{,}400}{333{,}436} = €0.0107\ /\ kWh \quad (35)$$

From grid prices found in (Eurostat, 2017) and the fact that in order to be profitable, a storage system must have a cost of energy between the difference of generation prices in specified timezones, the under study system, exhibits a $COE_{(2)}$ less than this difference, thus a wind-powered pumped-storage system using WARPs is feasible.

The total cost for the pumped-storage combination (without land acquisition, maintenance on the pump-generator, and some major construction) can be estimated as:

$$COE_{(1)} + COE_{(2)} = €0.0367\ /\ kWh \quad (36)$$

The results using the power law ratio are very close with a different economic analysis used for hydropower existing power plants, in other papers described by the formula used by (Gordon, 1978):

$$C_T = 9{,}600\ kW^{0.82}\ H_R^{-0.35} \quad (37)$$

where C_T is the equipment cost, kW is the total plant capacity in kilowatts; and H_R is the rated head in meters. This equation gives satisfactory equipment cost estimates for a plant capacity range from 50 kW to 40,000 kW, with the exception of sites with less than 3.7 m of head and high flows.

This equation with the use of the power law ratio can be transformed as:

$$\text{Cost of eq. a} = \text{Cost of eq. b}\left(\frac{\text{capac.eq.a}}{\text{capac.eq.b}}\right)^{0.64} \quad (38)$$

which gives similar results.

5.2 Case B: WARP GT Syros

In the case of WARP-GT for the island of Syros we follow the same process as in case A. Using the data by (Weisbrich et al., 1995), we know that for $\bar{v} = 5.8\ m/s$ and for 11 module per unit, the total initial capital cost is €30,895,000. For $\bar{v} = 8.0\ m/s$ with the same number of modules per unit, the total initial capital cost is €18,220,000.

The power correlation for a 50 module per unit, of a 47.3 MW average capacity power plant, for mean windspeed of $\bar{v} = 7.5\ m/s$ has a total initial capital cost of €20,215,000. For a 50.115 MW average capacity power plant, but with 11 module per unit, the total initial capital cost, for $\bar{v} = 7.5\ m/s$ is computed to be €20,300,000.

Having 11 identical WARP-GT the initial capital cost is:

$$ICC = (3{,}500)^{0.8}(300)(11) = €2{,}260{,}000 \quad (39)$$

To annualize the ICC we multiply it with an annualized factor α given by the formula mentioned before for case A. In this case, n = 10 years, i = 12%, u = 5.7%, results in $\alpha = 0.102$ Hence the annualized investment cost is:

$$A = €(2{,}260{,}000)(0.102) = €230{,}000 \quad (40)$$

Table 4 summarizes the main I&O&M figures. Mean power as percentage of the installed power is:

$$\frac{(420{,}000)(11)}{(3{,}300)(8{,}760)}100\% = 15.9\% \text{ or } 0.159 \quad (41)$$

The decrease in the mean power compared with case A gives us a good opportunity to note that a larger installation does not necessarily means more mean power. The benefit to cost ratio for the specific installation is calculated in Equation (43), and gives a result greater than 1, suggesting that the investment is profitable.

$$B/C_{ratio} = \frac{(0.09945)(420{,}000)(11)}{(242{,}000)} = 1.9 > 1 \quad (42)$$

For the WARP system following the same procedure the results can be seen in Table 4.

Table 4: WARP System and COE for the Island of Syros - 3,300 kW Wind Power Production - 7.5 m/s mean windspeed - 5 module.

No. of Units	11
kW / Unit	300
Total ICC (Initial Capital Cost)	€2,260,000

Table 4: WARP System and COE for the Island of Syros - 3,300 kW Wind Power Production - 7.5 m/s mean windspeed - 5 module (cont.).

Cost per kW	€3,500
Cost per Unit	€332,000
Cost per Module	€49,000
$A_{O\&M}$ Cost	€12,000
Annual Energy Production	4,600,000 kWh/yr
Cost-of Energy	€0.052/kWh
B/C_{ratio}	1.9>1 (profitable)
A_{rev}	€4,500,000
SPP	5.1 years

6 CONCLUSIONS

The Weibull distribution has been developed and applied for predicting the performance and the reliability of small autonomous systems consisting of WARP and WARP-GT. Applications in wind power plants using two examples show SPP from 5.1 to 5.3 years. While these payback periods are somewhat long compared with convention energy systems, for renewable energy they are sufficiently promising to justify further investigation.

The use of a combined pumped-storage wind-powered facility has been developed in a large scale system using a modular windmill consisting of a total wind capacity of 7.5 MW. An application of this system was made using a Greek island as an example, while its wind characteristics had already been given in a previous paper. Despite the fact that the difference of the day-time generation cost and the night-time generation cost is not large, the results of this large scale system show that this investment could be profitable. Hence as a system, this combination can be applied at many Greek islands in the summer periods, where usually there is an increase of the load demand. The use of this storage energy for the peak load demand would then reduce or even replace fossil fuel, which is costly at the Greek islands while an economic analysis based on a power law ratio could be applied.

ACKNOWLEDGEMENTS

This research was funded by the EC under the FP7 RE-SIZED 621408 (Research Excellence for Solutions and Implementation of Net-Zero Energy City Districts) project.

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