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Reverse Engineering and Design of a Windmill Pumping System suitable for Wind Conditions: A Case Study in a Suburb of Tajoura, Libya

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Abstract: Water-pumping windmills are reliable alternatives to provide water in some areas isolated from the electricity network, especially those with poor wind sources that are insufficient to operate wind turbines to generate electricity. The successful design of windmills for water pumping requires careful study of many variable parameters depending on the wind pattern and topography of the site. However, in this study, the researchers relied on the application of an integrated approach between the Forward Engineering (FE) and Reverse Engineering (RE), with the aim of obtaining a 3D CAD model of a water pumping windmill system. This 3D model will be the basis for manufacturing the windmill prototype that will be installed at a pilot site in a suburb of the city of Tajoura within a research project. The FE activities cannot be neglected when applying RE for the successful manufacturing of the windmills. The wind data recorded at the Center of Solar Energy Research and Studies (CSERS) for several years was used for calculating daily and monthly average wind speed and studying the daily wind pattern. The analysis of the collected wind data showed that the minimum and maximum daily average wind speed at Tajoura varies from 2.35m/s to 4.69 m/s, and the annual average wind speed is 3.24m/s. Among the Forward design activity is estimating the wind resources available at the site for sizing the system to provide the site water requirements of 5 m^3/day. From this point on, a commercial water-pumping windmill of 4.88m (16ft) and a standard tower height of 12m was chosen to be the target of a RE application to obtain a CAD model. RE is accomplished in three phases: digitizing the component (part), processing the measured data, and creating the CAD model. To adopt the 3D model for all parts, they must be compared with the original scanned data using Deviation Analysis in CATIA. After adopting the 3D models of all the system components, the 3D assembly models were created based on the

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integrated approach between RE and FE. Finally, it is worth noting that the windmills for water pumping could not be manufactured solely by just applying reverse engineering.

الهندسة العكسية وتصميم منظومة طواحين الهواء لضخ المياه ملائمة لظروف الرياح المحلية: دراسة حالة في إحدى ضواحي تاجوراء، ليبيا

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ملخص: تعد طواحين الهواء التي تعمل بضخ المياه بدائل موثوقة لتوفير المياه في بعض المناطق المعزولة عن شبكة الكهرباء، خاصة تلك التي تعاني من ضعف مصادر الرياح التي لا تكفي لتشغيل توربينات الرياح لتوليد الكهرباء. يتطلب التصميم الناجح لطواحين الهواء لضخ المياه دراسة متأنية للعديد من المعلمات المتغيرة اعتمادًا على نمط الرياح وتضاريس الموقع. في هذه الدراسة، اعتمد الباحثون على تطبيق نهج متكامل بين الهندسة الأمامية (FE) والهندسة العكسية (RE)، بهدف الحصول على نموذج (CAD) ثلاثي الأبعاد لنظام طاحونة ضخ المياه. سيكون هذا النموذج ثلاثي الأبعاد أساسًا لتصنيع النموذج الأولي لطاحونة الهواء التي سيتم تثبيتها في موقع تجريبي في إحدى ضواحي مدينة تاجوراء ضمن مشروع بحثي. لا يمكن إهمال أنشطة (FE) عند تطبيق الطاقة المتجددة للتصنيع الناجح لطواحين الهواء؛ تم استخدام بيانات الرياح المسجلة في المركز الليبي لبحوث ودراسات الطاقة الشمسية (CSERS) لعدة سنوات لحساب متوسط سرعة الرياح اليومية والشهرية ودراسة نمط الرياح اليومي. أظهر تحليل بيانات الرياح التي تم جمعها أن الحد الأدنى والحد الأقصى لمتوسط سرعة الرياح اليومية في تاجوراء يتراوح من 2.35 م / ث إلى 4.69 م / ث، ومتوسط سرعة الرياح السنوي 3.24 م / ث. من بين أنشطة التصميم المستقبلي تقدير موارد الرياح المتاحة في الموقع لتحديد حجم النظام لتوفير متطلبات المياه بالموقع البالغة 5 متر مكعب / يوم. من هذه النقطة فصاعدًا، تم اختيار طاحونة هوائية تجارية لضخ المياه يبلغ ارتفاعها 4.88 مترًا (16 قدمًا) وارتفاع برج قياسي يبلغ 12 مترًا لتكون هدفًا لتطبيق (RE) للحصول على نموذج (CAD). يتم إنجاز الطاقة المتجددة على ثلاث مراحل: رقمنة المكون، ومعالجة البيانات المقاسة، ثم إنشاء نموذج CAD. لاعتماد النموذج ثلاثي الأبعاد لجميع الأجزاء، تمت مقارنة كل جزء بالبيانات الأصلية المسوحة ضوئيًا باستخدام تحليل الانحراف في (CATIA). بعد اعتماد نماذج ثلاثية الأبعاد لجميع مكونات النظام، تم إنشاء نماذج التجميع ثلاثية الأبعاد بناءً على النهج المتكامل بين (RE) و (FE). واخيراً، تجدر الإشارة إلى أن طواحين الهواء الخاصة بضخ المياه لا يمكن تصنيعها فقط من خلال تطبيق الهندسة العكسية.

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***Keywords*:** *Windmills, Rotor, Wind Speed, CAD, CATIA, Mesh, Point cloud, FE, RE, Laser Scanning.*

1. INTRODUCTION

The mechanical windmills in remote areas are a good, feasible option for pumping water. The design and evaluation of stand-alone renewable energy systems, such as windmills for pumping underground water, is a challenge and a possible alternative in many situations. Even at lower wind speeds, the wind-mechanical pumps can be sufficient to economically produce feasible energy for pumping water [1,2,3]. Reverse Engineering (RE) is the opposite of Forward Engineering (FE). It is a process that includes measuring, analyzing, and testing to reconstruct the mirror image of an object or retrieve a past event. RE is a technology of reinvention, a road map leading to reconstruction and reproduction. It is also the art of applied science to preserve the design intent of the original part [4,5]. There is no way to manufacture a water-pumping windmill successfully using the RE technique if it is applied directly to a physical windmill without precisely evaluating the site's wind resources and choosing the appropriate size of the wind water pumping system. Unfortunately, there is no explicit power curve for water-pumping windmills. Since the windmill and site characteristics cannot be separated, as is usually the case with wind turbines, the output curve of the water pumping windmill depends on both the feature characteristics of the windmill and the wind system at the site chosen to install the windmill. Identifying the wind speed at a specific location or area is complex due to the random nature of the wind, which does not follow any known statistical distribution. Therefore, collecting wind data for many years and using probability density functions (PDFs) is best to characterize the wind speed for a specific location [6,7].

The Weibull and Rayleigh functions are the most commonly used PDFs to study wind characteristics at the target location [7,8,9]. Reverse engineering provides powerful tools in the CATIA V5 (now referred to simply as CATIA) environment [10], enabling flexibility in manipulating point clouds and meshes to optimize them into high-end 3D surface shapes. RE Integrated in the CATIA design environment helps reduce project costs and is more efficient and effective by employing faster and simpler design iterations. This study aims to apply the reverse engineering process using CATIA to build a 3D CAD model of the water pumping windmill system based on the site wind characteristics. This model will be used later to manufacture the prototype of the water pump locally as a pilot project, in order to pave the way for the manufacture of the many pumping windmills to provide water for irrigation, farms, homes, and community in remote areas of the State of Libya, commensurate with the local manufacturing capabilities.

2. LITERATURE REVIEW

Wind energy can be exploited through various ways, e.g., wind turbines and various types of windmills. Many research studies have demonstrated the economic feasibility of using windmill-powered water pumps to pump water mechanically. Badran [11] reported that mechanical windmills are characterized by low cost, ease of design, and the potentiality of being locally manufactured in most third-world countries. Moreover, these systems contribute to a remote area's social and economic development and are more affordable than other systems, including conventional pumps that operate with electricity or diesel fuel. Elamouri presented perspectives of the mechanical wind pumping in eight synoptic sites distributed in the Tunisian south. Based on meteorological data recorded for five years, the wind resource analysis showed that the south of the country has a good wind potential for the mechanical wind pump system [12].

Odesola and Adinoyi [13] in the study they conducted, a model was designed and implemented for pumping water using a Rotor diameter of 2.14 meters and a solidity area of 3.733 m^2, at a location where the wind speed was 2.5m/s, at the height of 16 meters from the ground. The performance tests for this windmill showed that the water pumping rate for irrigation might range from 3.4 to 6.44 liters/min. As a guideline, effective electricity generation from wind energy requires an average wind speed greater than 2.5m/s [13]. However, lower wind speeds can be sufficient for mechanical wind pumps [1,3,14]. Even at an average wind speed of 2.5m/s, wind-mechanical pumping can still be economically feasible [3,14]. The proven reliability of classical wind pumps can be important, especially for pumping from deep wells [2]. The cost of water from a windmill water pumping system is susceptible to the monthly average wind speed. In addition to the many studies conducted on the design of these systems and wind energy to pump water, many other studies have applied Reverse Engineering to manufacturing new products that are somehow identical or improved. Sokovic and Kopac [15] in their study, explained some possibilities of use and benefits of utilizing the RE methodologies and techniques in the production process, especially in the case when parts without 3D CAD support exist. Zhang described the Reverse Engineering process in his study, from object digitization and CAD model reconstruction to NC machining [16]. The measurements were obtained by scanning the physical product, and a CAD model was created for the mold. The mold was manufactured, and a good result was obtained. Kacmarcik et al. [17], in their study, presented an example of a Reverse Engineering process involving the use of a modern measuring device, optical 3D scanner, and software for scan data processing, Computer-aided design (CAD), and Finite Element Method (FEM).

3. METHODOLOGY

The methodology presented in this paper involves an integrated approach between the FE and the RE to obtain a 3D CAD model of water pumping windmill system. Both FE and RE activities were carried out:

(i) Forward Engineering (FE) activities:

These activities related to the use of the wind data collected over several years (2005-2016) at CSERS for:

- Fitting the wind data using the Weibull distribution to characterize the wind speed and evaluation of wind resources.
- Determining the monthly and hourly average wind speed values during the day (Diurnal wind pattern).
- Selecting the site and sizing the windmill according to the amount of wind energy available at the site.

(ii) Reverse Engineering (RE) activities:

The various activities of the RE process in designing and constructing a CAD model of an existing classic commercial windmill were carried out as follows:

- Digitizing the component using Baces3D portable laser scanning system for obtaining dimensional data.
- Processing the measured data,
- Creating the final surfaces by overlapping the point cloud with the mesh, was done by making several operations using the CATIA's Digitized Shape Editor (DSE).
- The surface models of the scanned components were created by Quick Surface Reconstruction workbench (QSR) in CATIA.
- The solid 3D model of the Rotor Sail was created by the Part Design workbench (PD) in CATIA.

4. THE MAIN COMPONENTS OF WATER PUMPING WINDMILLS

The most important component of the windmill water pump is the Rotor and its parts, as shown in Figure (1). The Rotor with the gearbox and the tail are carried by the tower to a suitable height away from the air turbulence that is caused by the terrain, trees, and barriers on the earth's surface. Through the gearbox mechanism, the circular motion of the shaft is converted into a reciprocating motion, which is transmitted to a piston water pump through the main shaft. A water tank with a suitable capacity and a piping system to transport water from the source to the users is an integral part of the system.

5. DATA PRESENTATION

Wind speed data were collected from CSERS located in Tajoura; data were organized in order to investigate the wind conditions in Tajoura and select the appropriate commercial windmill to apply the RE approach.

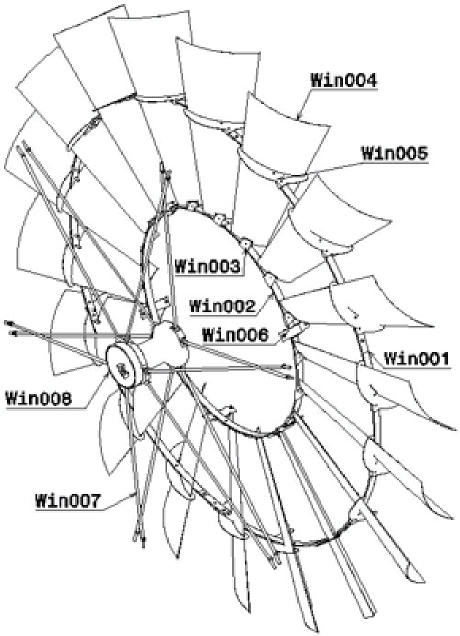
$$p_0 = N_{\nu} e^{-\nu_{p0}/KT} \quad \text{.........} \quad (4)$$

This area has enough wind availability per day and some underground water reserves.

Being located near agricultural or pastoral areas, the windmill water pumping finds great opportunities for its use in these areas. Reliability, accuracy, and calculating wind speed averages of the site data are a prerequisite for the success of the windmill since a small error in the wind speed can cause a much larger error in the calculated power because the power in the wind is proportional to the cube of the wind speed. Wind speed data for the selected location were prepared based on the monthly averages and daily averages for 11 years from 2005 to 2016 at CSERS to be used for the calculations and analysis.

6. VIABILITY OF WIND PUMPING

The quantity of wind available at a site (location) is affected by the overall wind patterns, the general characteristics of the land's topography surrounding the site, and whether the location is open or has obstacles such as trees or buildings [18]. While the data available for a region are helpful for the first impression of wind resources, accurate calculations, and analysis is inevitable. In addition to the monthly average values shown in Figure (2), the hourly average wind speed values during the day must be considered for the collected data at the CSERS Climate Station in 2017, as shown in Figure (3). Usually, the wind speed on most days of the year exceeds the annual average from midday until 04:00 pm. Still, in general, the wind speed begins to rise from 9:00 am and continues to increase until it reaches its highest levels and then decreases at 6: 00 pm. That means the windmill will often be standing still during the late night and early morning but will mostly run during the rest of the day. The windpump design should satisfy the daily pumping requirements during those hours of strong winds a day.



Part No.	Description	Part No.	Description
Win 001	Outer Rotor Bands	Win 005	Sail ribs
Win 002	Inner Rotor Bands	Win 006	Cross Ties
Win 003	Sail Ties	Win 007	Rotor Arms
Win 004	Sails	Win 008	The Hub

Figure (1). The main components of the windmill Rotor.

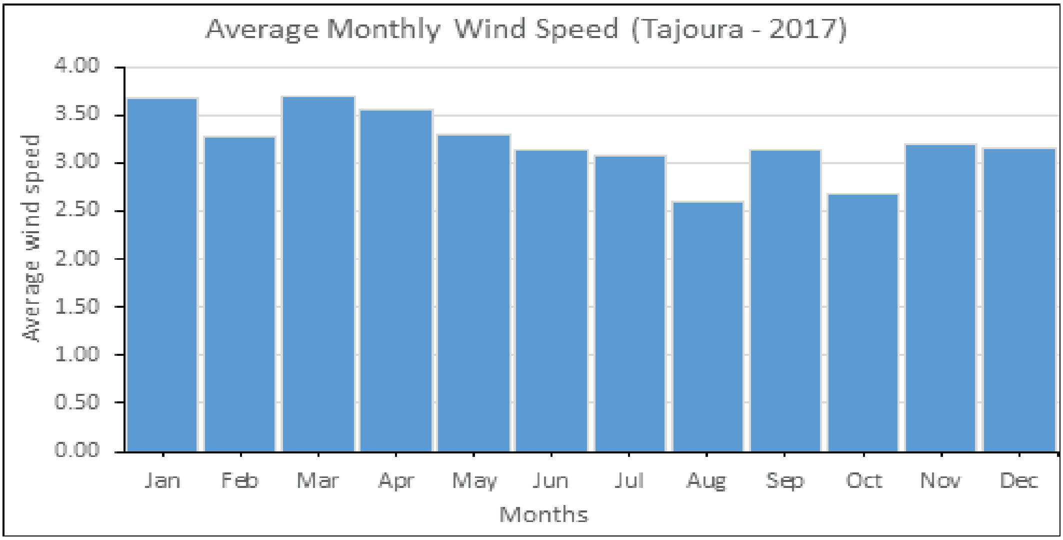


Figure (2). Monthly variations of wind speed, Tajoura (2017).

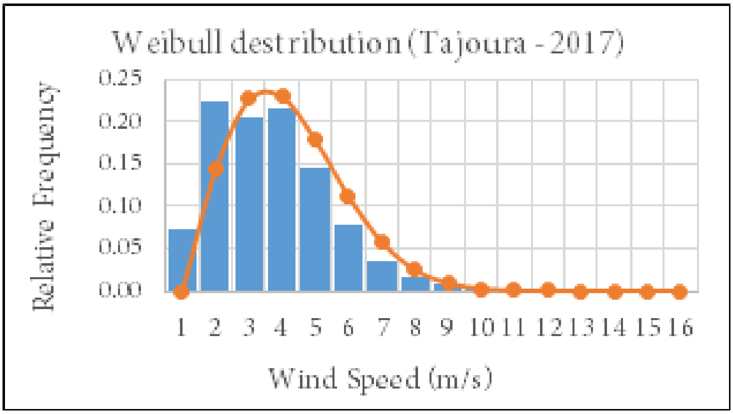


Figure 3. Hourly variations of wind speed (Diurnal wind pattern), Tajoura (2017).

From what was mentioned earlier, one can deduce that the hours during which the wind speed approaches the annual average during the day are 8 to 9 hours, so to improve the starting behavior, it is very important to reduce the time that the Rotor starts to rotate by balancing the weight of the pump rod, or sacrificing some water output, in order to reduce time to start running the windmill using a starting nozzle in the piston pump, the water displaced in the discharge pipe leaks through the nozzle.

7. WIND SPEED DISTRIBUTION

The most widely used PDF to fit wind data is the Weibull distribution [7,19-22], which is defined as

$$f(\upsilon) = \frac{k}{c}\left(\frac{\upsilon}{c}\right)^{k-1} e^{-\left(\frac{\upsilon}{c}\right)^{k}} \quad \text{.......} \quad (1)$$

for ($\upsilon > 0$, $k > 0$ and $c > 0$).

where *f(v)* is the probability of observing wind speed (*v*), the scalar quantity (*k*) is the shape parameter, and (*c*) is the scale parameter in m/s. A special case of Weibull distribution when *k*=2 is called the Rayleigh distribution. Weibull distribution function fits the wind speed variation better than the Rayleigh distribution function [23]. In this study, the selected method of estimating Weibull parameters is the least square method (LSQM). The estimation procedure is as follows[24-25].

The LSQM, also known as the graphical method, is based on logarithmic transformations applied to the Weibull cumulative distribution function *F(v)* and, thus, can be represented by a straight line:

$$y = M_x + Y_0 \quad \text{.......} \quad (2)$$

And:

$$y = \ln(-\ln(1 - F(\upsilon))); \; x = \ln(\upsilon) \quad \text{.......} \quad (3)$$

The Weibull parameters can be achieved from:

$$k = m; \; c = e^{-Y_0/M} \quad \text{.......} \quad (4)$$

And:

$$M = \sum_{i=1}^{n}(x_i - x_m)(y_i - y_m) / \sum_{i=1}^{n}(x_i - x_m); \; Y_0 = y_m - Ax_m \quad \text{.......} \quad (5)$$

where and are the mean values of x & y, respectively; and & , are the values obtained using Equation (2) with each wind speed data set.

By applying the least squares (the graphical method) such as shown in Figure (4) for CSERS wind speed data in 2017, the Equation of the line is:

$$y = 1.99x - 2.3 \quad (6)$$

Thus, based on Equation (4), Weibull parameters can be calculated as k=1.99 and c=3.4.

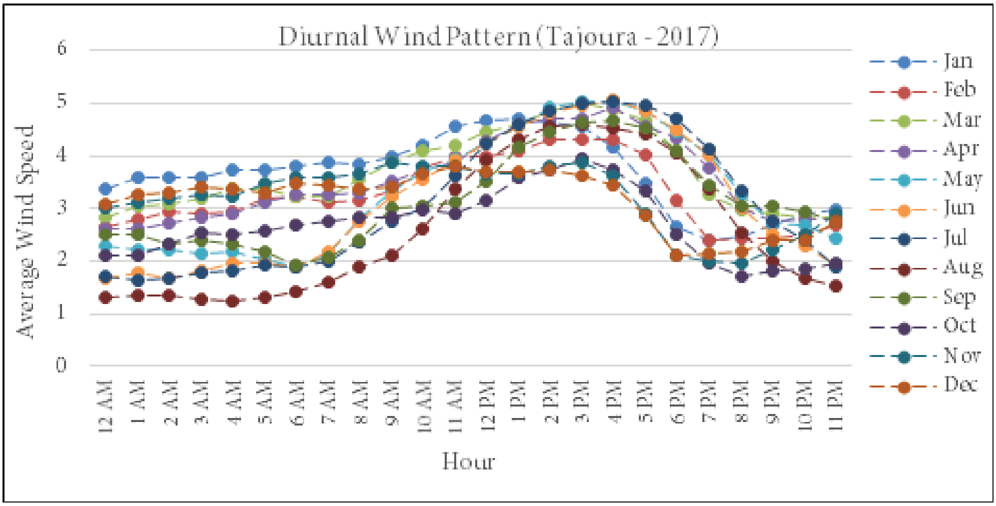


Figure 4. Graphical method of determining Weibull parameters.

The wind distribution function at Tajoura for Weibull parameters is shown in Figure (5).

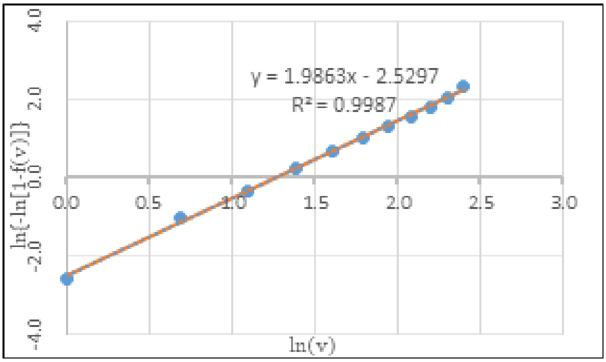


Figure 5. Weibull distribution to Tajoura (2017) for k=1.99, and c=3.4.

8. SELECTING THE SITE AND SIZE OF THE WINDMILL

In this study, calculations were made in a simple way to determine the proper rotor size for the location where the windmill will be installed. These calculations used in the design of the windmill were made to examine whether the size of the Rotor to which the RE will be applied is appropriate for the site.

The steps to be followed in selecting the optimum size of a water pumping windmill for a site are:

8.1. Site selection

The feasibility of a windmill is largely affected by its site. The site must have enough wind power to move the windmill and must be away from any obstruction that might cause turbulence. The climatic condition of the site should be examined for over a year and recorded on a wind map which is then used to analyze the site's suitability [26-28]. The Rotor should be tall enough to ensure it's far above the obstacles.

Identifying and determining the site of the windmill understudy was done. The analysis on the site to assess its suitability and the findings are as follows:

- The winds speed of Tajoura varies from 2.35 m/s to 4.69 m/s, and these were the minimum and maximum daily average wind speeds recorded from January to December for eleven years, with an annual average wind speed of 3.24 m/s.
- The site (location) of the windmill is strategically away from tall buildings and trees; therefore, minimal obstruction of the wind. The selected standard tower height of 12m is sufficient to lift the Rotor over the isolated trees in the surroundings.

8.2. Determining the water demand (Q_p)

The determination of the water demand (Q_p) depends on the total number of site beneficiaries and the daily per capita water. Water consumption in the Center for Solar Energy Research and Studies is constant. The water pumping requirements are estimated at 5 m^3/day, which satisfies the needs for human uses and garden irrigation.

8.3. Determination of the hydraulic power

The hydraulic power required (P_{hyd}) to lift water from the source to the storage tank is calculated based on Equation (7) [28]:

$$P_{hyd} = Q_p \rho_w g H \quad (7)$$

where:

Q_p= the water demand.

ρ_w=water density (1000kg/m^3).

g = acceleration due to gravity (9.81m/s^2).

H = the total discharge head (m).

The total discharge head is found by adding the depth of the water level in the well and the height of the tank (93m).

The delivery pipe length is (96m), the pressure loss in the pipes is about 10% of the total head [2]. From that, the head loss in the delivery pipe is 9m, in addition to the total discharge head (H). The average hydraulic power requirement (P_{hyd}) is 57.8W calculated based on Equation (7).

Table (1) shows various losses that have to be considered for determining the average hydraulic power requirement [2,29,30].

The average efficiency of the pump is 70%. The average efficiency of the shaft from the gearbox to the pump is 95 %. The average efficiency of the gearbox is given as 99%, which is the actual efficiency of the gears. The efficiency of the horizontal shaft between the Rotor and gearbox is given by 95%.

The amount of the average hydraulic power requirement from the wind (P_{hyd}) is 92.4W.

Table (1). Power losses in the windmill.

Factor	Typical Efficiency
Rotor to shaft	92-97%
Shaft to gearbox	93-96%
Gearbox	99%
Pump	60-75%

8.4. Wind power potential determination

The wind power potential (is given as the specific wind power or power per unit area [28,29,31]. It is calculated by using the Equation:

$$P_{wind} = \frac{1}{2}\rho_a V^3 C_p \quad (8)$$

where:

= air density(ρ_a).

V = the wind velocity.

The roughness of the terrain (isolated buildings, small trees) is estimated to be 0.25m taken from the Davenport classification of effective terrain roughness [32-35]. By using Equation (9), the data for 10m above terrain height are converted into 12m, as the standard tower height (12m) that was chosen.

$$\frac{V_z}{V_{zr}} = \frac{\ln\left(z/z_0\right)}{\ln\left(z_r/z_0\right)} \quad (9)$$

where:

z = height above the ground surface (m); z_r= reference height (m); z_0 = surface roughness length (m); V_{zr}= the wind speed at the reference height and V_z = wind speed at any height z.

Table (2) shows the results for the understudy windmill system.

The site is practically at sea level, and the density of air is assumed to be 1.2 kg/m^3. In the last column, the specific wind power is calculated using Equation (8) multiplied by the Power Coefficient, assuming the maximum practical value of Power Coefficient (C_p) is 0.3.

8.5. Reference area and size of the windmill

The ratio of the hydraulic power of each month divided by specific wind power potential for the same month [28] has the dimension of the area and is referred to as the reference area (:

$$R_a = \frac{P_{hyd}}{P_{wind}} \quad (10)$$

The Rotor diameter is given in Equation:

$$D_r = \sqrt{\frac{4R_a}{\pi}} \quad (11)$$

8.6. Determination of the design month

The design month is found by calculating the ratio of the hydraulic power requirement to the wind power resource for each month. The month in which this ratio is a maximum is the design month. The monthly averages of wind speed (Table 3) were recorded at the height of 10 meters and converted into 12m (at the hub height) from the surface of the earth at the Center for Solar Energy Research and Studies in Tajoura, where the windmill will be installed. From Table (3), August and October are the design months with $R_a = 17\ m^2$. Hence, by using Equation (11), the Rotor diameter is: 4.7 m

Table (2). Determination of specific wind power.

DETERMINATION OF SPECIFIC WIND POWER (P_{wind})				
Location : Tajoura			Height above sea level: 50m	
Hub height: 12m			Terrain roughness: 0.25m	
Combined correction factor for Hub height and roughness: 1.05				
Month	Average wind speed at 10m (m/s)	Average wind speed at Hub height (m/s)	Density of air (kg/m³)	Specific wind power (W/m²)
Jan	3.5	3.7	1.2	8.9
Feb	3.53	3.7	1.2	9.2
March	3.47	3.6	1.2	8.7
April	3.55	3.7	1.2	9.3
May	3.42	3.6	1.2	8.3
June	3.34	3.5	1.2	7.8
July	2.99	3.1	1.2	5.6
Aug	2.97	3.1	1.2	5.4
Sept	3.06	3.2	1.2	6.0
Oct	2.97	3.1	1.2	5.4
Nov	3.03	3.2	1.2	5.8
Dec	3.12	3.3	1.2	6.3

The nearest available standard rotor diameter is 4.88m (16ft), as was reported by Clark [36] and Aermotor windmill company [37], which was selected for the RE process in the present study, would be suitable for the site where the windmill will be installed [37,38].

Table 3. Sheet for identification of design month.

DESIGN MONTH					
Location : Tajoura (CSERS)					
Month	Average hydraulic power (P_{hydr}) (W)	Average wind speed at Hub height (m/s)	Specific wind power (P_{wind}) (W/m²)	Reference area (P_{hydr}/P_{wind}) (m²)	Design month
Jan	92.4	3.7	8.9	10.4	
Feb	92.4	3.7	9.2	10.1	
March	92.4	3.6	8.7	10.6	
April	92.4	3.7	9.3	9.9	
May	92.4	3.6	8.3	11.1	
June	92.4	3.5	7.8	11.9	
July	92.4	3.1	5.6	16.6	
Aug	92.4	3.1	5.4	17.0	⬅
Sept	92.4	3.2	6.0	15.5	
Oct	92.4	3.1	5.4	17.0	⬅
Nov	92.4	3.2	5.8	16.0	
Dec	92.4	3.3	6.3	14.6	

8.7. Pump selection

The choice of a small pump enhances availability but reduces output. In matching a pump to a windmill, one must establish the best possible compromise between output production and availability [39]. Referring to some diagrams and tables found in reference [2] to determine the volume of water pump suitable for a classical back-geared windmill with deep well pump, in this case of a Rotor diameter of 4.88m (16ft); wind speed average of the critical month of 3.1m/s:

- The effective stroke volume of 0.755L.
- Assuming a volumetric efficiency of 90%, the geometric stroke volume is 0.84L.
- The maximum stroke available for the 16ft windmill is 288,93mm .
- Through all of this, it is possible to find the right pump with a diameter of 56mm; this is close to one of the pumps of the standard range in use, 2.5in (63.5 mm).

To check the suitability of the pump to the water requirements for 9 hours/day when the windmill is running with 11 strokes/min, the water

requirements = 0.84x11x60x9=4989.6 L/day.

These large quantities of water will be in the critical months of August and October, which are appropriate quantities, and expected to be an excessive water production in the remaining months that will return to the well through a pipe designated. Equation (12) can be used to find the geometric volume displaced [28] by the piston (of a piston pump diameter in each stroke (s).

$$V_s = \frac{1}{4}\pi D_p^2 s \qquad (12)$$

Since the flow rate provided by the wind is irregular, water is usually required at a relatively high flow rate during short periods of the day. The storage and distribution of water is an important part of pumping systems; the main purpose of a storage tank is to store surplus water during days of strong wind for later use when there is less wind. A tank with a capacity equivalent to 3 days of water requirement is available on site (about 15m^3) and will be used within the system.

9. HARDWARE AND RE SOFTWARE

The work for obtaining dimensional data of the windmill components is carried out with BacesSCAN portable laser scanning system (Non-Contact Technique) at Trucks and Buses Company (T.B.Co.), as shown in Figure (6). It is composed of Baces3D, a three-coordinate measuring arm (7 axis M100). The scanner's output is the 3D scan data as a point cloud or dense triangle mesh. This data serves as a visual sketch and will require manipulation before it becomes a final CAD file.

Figure (6). BacesSCAN portable laser scanning system.

The beginning for further modifications of scanned surfaces and the creation of a 3D CAD model is the transformation of point's cloud from Baces3D software into 3D software. This was realized by a universal file format for data transfer between various 3D software solutions (IGES). To create the final surface by overlapping the point cloud with a mesh, it is necessary to make several operations using CATIA's Digitized Shape Editor (DSE).

10. THE RE PROCEDURE

The RE process can principally be seen as a process chain that is composed of the following main operations:

10.1. Digitization of the component

The problem of optical scanning systems is high shine of surfaces like chrome-plated surfaces or also black surfaces that do not reflect laser ray [40]. All the target components have been sprayed with temporary matte powder to improve scan accuracy and avoid uncontrolled laser ray scattering. Using the BacesSCAN portable laser scanning system all the target parts of the windmill were scanned. In Figure (7), the Baces3D arm is shown at the moment of its use during scanning the Sail. The point cloud files obtained from the Baces3D software digitizing machine were transferred to the CATIA used for performing the point processing operations and the CAD model reconstruction.

Figure(7). The BacesSCAN portable laser scanning system is shown at the moment of its use.

10.2. Processing of the measured data

The process turns the point cloud or mesh that was received from the scanner into a polygonal model; the resulting mesh is cleaned up and smoothed to retain its required shape and accuracy. The preprocessing work was carried out as follows:

- **Removing error points:** these error points can be removed by Remove Command in DSE CATIA.
- **Filtering points:** by applying the Filter Command in DSE CATIA, which displays only the sufficient number of points needed to determine the geometry of the surfaces of the part.
- **Creating and repairing mesh**: mesh is created by the command of Mesh Creation of DSE CATIA. The achieved mesh has some discontinuity and large holes as shown in Figure (8). The holes in the mesh are repaired with the Fill Holes, Mesh Smoothing, and Mesh Cleaning commands in the DES workbench in the CATIA. Figure (9) shows the repaired mesh.

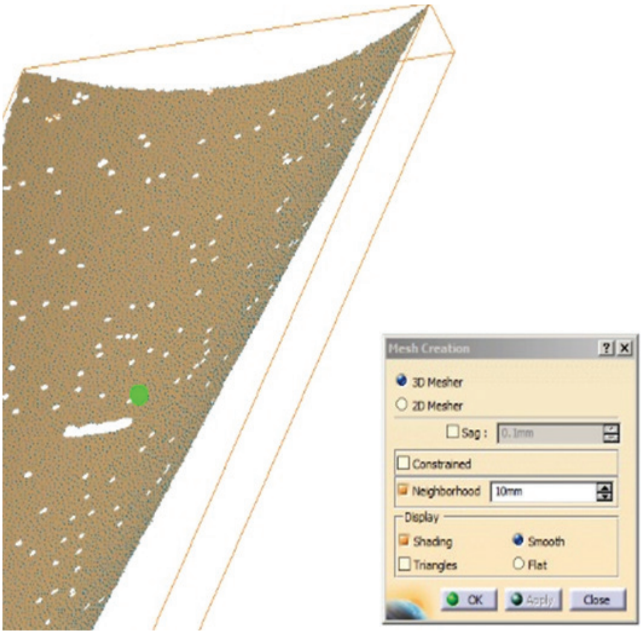


Figure (8). Mesh created by Mesh Creation command.

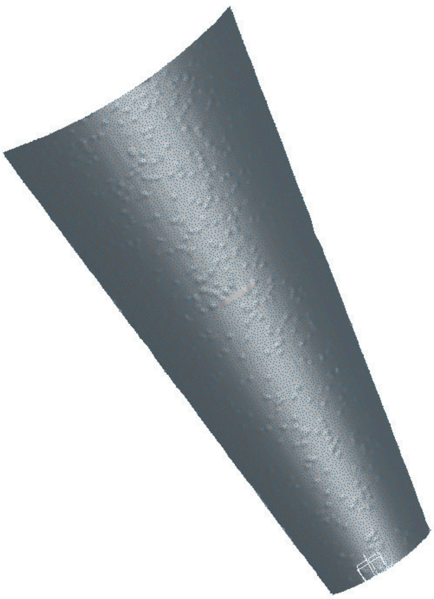


Figure (9). The repaired mesh of the Sail.

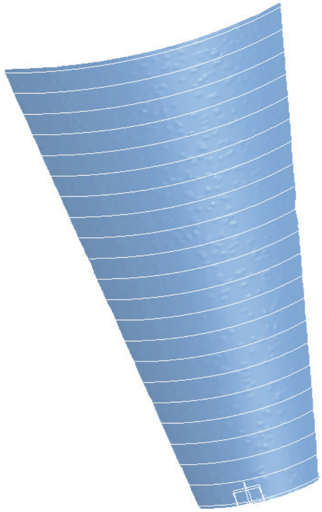


Figure (10). Planar curves on the repaired mesh.

10.3. Creation of a CAD model

The next step after repairing the digitized points is the creation (on these points) of the curves on the surfaces that form the geometric model of the part. To obtain good surfaces, it is preferable creating planar curves when possible, using the Planar Sections Command inside the DSE workbench in CATIA. Figure (10) shows planar curves that constitute the surfaces support on the repaired mesh.

At this point, the fundamental problem is the choice of surfaces to be used to interpolate the curves obtained to replicate the geometry of the physical piece as closely as possible.

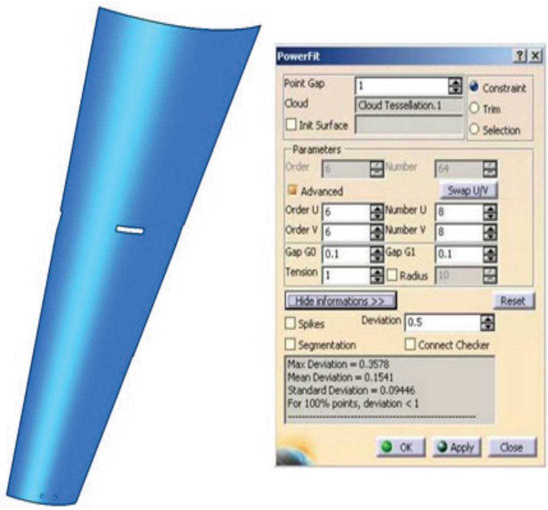


Figure (11). Final obtained surfaces of the Sail.

All the surfaces of the windmill parts are created by Quick Surface Reconstruction (QSR) in CATIA by Powerfit. From these obtained surfaces by the Powerfit Command in Figure (11), a solid 3D Sail model is formed using the Part Design in CATIA.

11. RESULTS AND DISCUSSION

11.1. Selecting the Site and Size of the Windmill

It is well known among the researchers, users, and manufacturers of the windmills industry, that the winds data collected is a prerequisite for the proper selection of the site and size of the windmill. Based on the meteorological data recorded at CSESR, the wind resource analysis showed that the winds speed of Tajoura varies from 2.35 m/s to 4.69 m/s, and the daily average wind speeds recorded from January to December for eleven years, with an annual average wind speed of 3.24 m/s. This average wind speed is appropriate since a minimum speed of 2.5m/s is needed for windmills, which means that the city of Tajoura has a good wind potential for the mechanical wind pump system. More detailed results were discussed in section 7 and 8. The site of the windmill is strategically away from tall buildings and trees; therefore, minimal obstruction of the wind. The wind resources at the site for sizing the system to provide the site water requirements of 5 m^3/day are available. The appropriate diameter of the rotor to supply the water demand on the site of 5m^3/day, from tubewell of diameter 250mm, and water level 90m was calculated as 4.7m. The closest size in the standard range is 4.88m (16ft), which was selected for practical purposes.

11.2. RE Process and Creation of CAD Model

Based on this rotor diameter, the researchers constructed both the RE and the CAD model of the rotor. A commercial water-pumping windmill of 4.88m and a standard tower height of 12m was chosen to be the target of a RE application to obtain a CAD model. As was discussed in sections 9 and 10, the reverse engineering process is accomplished in three phases: all the target windmill parts were digitized using the BacesSCAN portable laser scanning system, then point cloud files obtained from the Baces3D software digitizing machine were transferred to the CATIA used for performing the point processing operations, and finally, the CAD model was reconstructed.

11.3. Deviation Analysis

After succeeding in the completion of the CAD model of windmill parts, the finished part model is then compared to the original scanned data in DSE workbench in CATIA, which gives a detailed 3D Deviation Report (html file).

Deviation Analysis command in DSE of CATIA was used to perform a deviation analysis by comparing the point cloud data (gathered from scanning the part) with the final CAD model. Here the results of the Deviation Analysis of the Sail rib were only presented as an example, but the analysis was carried out on all other windmill components reverse engineered. The CAD model of the Sail rib was set as Reference and scanned data of it. A total of 6846 data points were tested for a 3D deviation check. The parameters for the test were as shown in Table (4).

Table (4). Sail rib Deviation Analysis Input Parameters.

Reference Data	Surface.1
Data To Measure	Mesh Creation.1
Accuracy	0.010
Only Orthogonal	0
Absolute	0

As around 100% of the points lie in the tolerance range of +/- 1mm, with a mean deviation of 0.00mm, and a standard deviation of 0.02mm, the design extracted is considered a good design. Table (5) gives a detailed deviation analysis of the data points. Figure (12) shows a graphical colored map to visualize the deviation analysis data and various annotations of the Sail rib.

Table (5). Deviation Analysis Statistic Result of Sail rib.

Total Number of Selected Points	6846
Number of Points Used in Computation	6846
Number of Points with Positive Deviation	555
Number of Points with Negative Deviation	209
Positive Maximum Deviation Value	0.20mm
Negative Maximum Deviation Value	0.15mm
Mean Deviation	0.00mm
Standard Deviation	0.02mm
Positive Mean Deviation	0.05mm
Negative Mean Deviation	0.02mm
Positive Tolerance	1.00mm
Negative Tolerance	1.00mm
Percentage In Tolerance	100.00

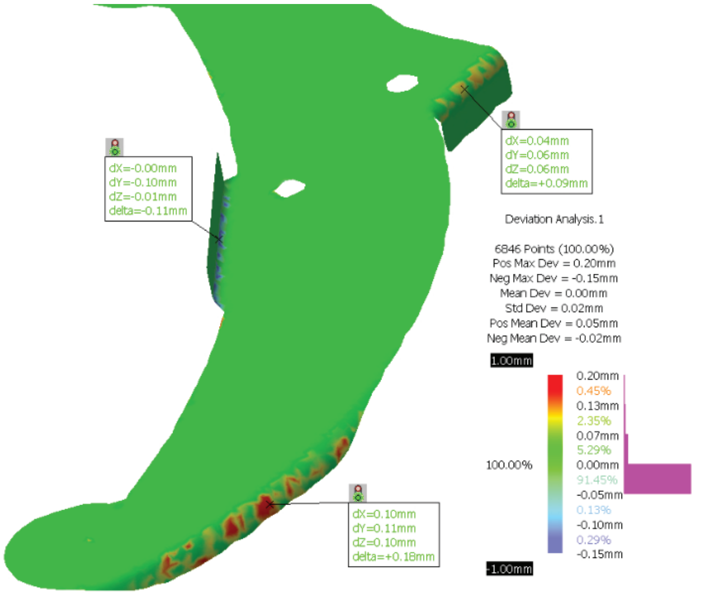


Figure (12). A snapshot of Sail rib deviation analysis.

In addition, this Figure shows the histogram of the data distribution where 91.45% of the deviation points data of the CAD surface from the original point cloud data lies between 0 and -0.05 mm. These results are the best results that were achieved after carrying out several checks and modifications of the model of Sail rib. In general, it is possible for another user to obtain better or less accurate results, as modification and fitting of surfaces using CATIA software depend on the user's skills.

11.4. 3D Models

After adopting the 3D models of the Rotor components as a result of the aforementioned deviation analysis, 3D CAD assembly and sub-assembly models of the windmill were prepared based on the existing physical water pumping windmill, as shown in Figure (13) of the complete Rotor assembly. However, to validate these 3D CAD assembly models, verification for fouling, overall interference dimensions, etc., was carried out before starting the prototype manufacturing.

Subsequently, the two-dimensional manufacturing drawings in such a case are among the most important output obtained from applying the RE for the windmill components. By using these drawings, many documents are prepared for the subsequent stages, such as the work plan document, the bill of materials, and the quality inspection documents.

All of these drawings and documents will be developed and modified when the prototype is manufactured and during the on-site test and development stage.

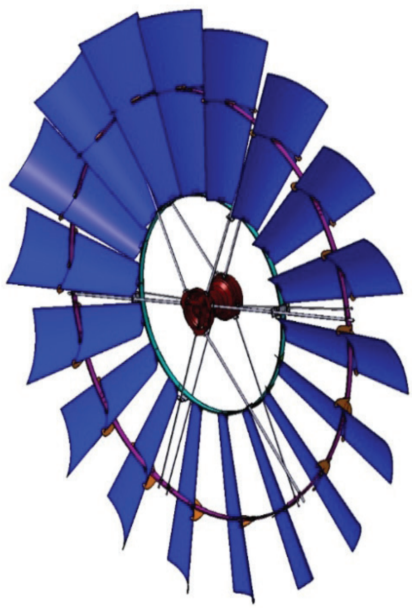


Figure (13). 3D-CAD assembly model of the Rotor.

12. CONCLUSIONS

The conclusions that can be briefly summarized from this research paper are as follows:

- Generally, from both the literature and this research study, the researchers concluded that the windmills for water pumping could not be manufactured solely by just applying the RE without FE, namely, (i) Determining water requirements, (ii) studying the wind characteristics, (iii) properly evaluating wind resources on the chosen site, and (iv) sizing the system.
- Wind speed data are evaluated, and it was found that the city of Tajoura has sufficient wind potential (wind speed ranging from 2.35–4.69 m/s) that can be used for water pumping.
- The appropriate diameter of the rotor to supply the water demand on the site of 5m^3/day, from tubewell of

diameter 250mm, and water level 90m was calculated as 4.7m, and the closest size in the standard range is 4.88m (16ft).

- The selected understudy mechanical windmill is suitable for the chosen site.
- A 3D CAD model of the wind water pumping system components was built using CATIA by applying RE and FE integration to an existing classic commercial windmill, according to the rotor size selected based on the available wind energy.

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