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CONCEPTUAL WIND POWER PLANT DESIGN FOR HIGHFIELD CAMPUS.

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Abstract

Wind energy is one of several renewable energy sources that would help shape the future power generation industry. In this paper, a wind power plant is suggested to meet 40 % of electricity consumption of Highfield Campus at the University of Southampton. After considering the environmental effects, cost analysis, efficiency, the location for the wind turbine was recommended to be on the coast of the Isle of Wight, making it an offshore plant. The system was designed with two wind turbines with an installed capacity of 1 MW each. The plant would help reduce the greenhouse gases emitted by fossil fuelled fired plants.

Keywords; Wind Power, Renewable energy, Wind speed, Design, Onshore.

1. INTRODUCTION

Due to environmental concerns, renewable energy sources are becoming more popular. Wind power is one of the most promising renewable energy source for the University of Southampton and the UK at large in terms of its cost and viability. In fact, wind power is one of the largest source of renewable energy in the UK, only second to biomass. The British Wind Energy Association (BWEA) now known as Renewable UK estimated that by 2020 the United Kingdom would have more than 28 GW of wind power capacity [1].

To generate wind power, a wind turbine is placed on a tower with its blades spinning under the influence of the wind. The turbines subsequently spin the rotor of a generator to generate electricity. To increase the output, multiple wind turbines are often connected in parallel to form a wind farm. Wind power farms could be either built onshore (inland) or offshore (in oceans/rivers). A summary of the advantages and disadvantages of these two arrangements of wind farms are shown in Table 1.

Table 1. Comparison of onshore and offshore wind farms. [2]

	Advantages	Disadvantages
Onshore	- Lower capital installation cost - Cheaper integration with the electrical-grid network. - Easy access to maintenance - Long period development results mature techniques.	- Limitation of large continuous areas - Injuries to birds - Lower wind speed, lower production per unit installed - More turbulence - Produce noise and visual issues - Inconvenient transportation
Offshore	- Convenient transportation for large-scale project by sea; - Availability of large areas; - Elimination of social and environmental issues; - Higher wind speed, thus the capacities increase; - Less turbulence,; - Lower wind shear, shorter tower available.	- Higher installation cost - Complex procedures of installation - Difficulties in maintenance

The basic components of a wind turbine is shown in Figure 1.

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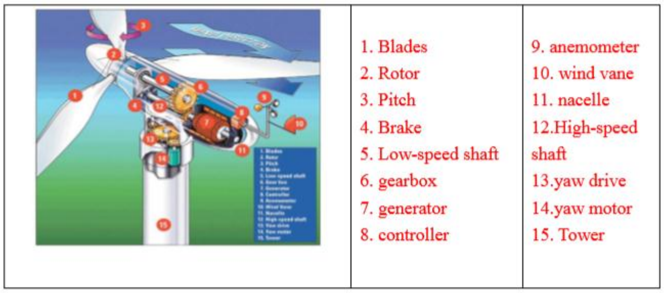

Figure 1. Components of wind turbine

This aim of this work is to design a wind power plant which would provide about 40%of electric power for the Highfield Campus. Specific aspects focused on are listed below:

(i) To determine existing electric power consumption amount in Highfield Campus,
(ii) To choose a proper site to build the wind farm
(iii) To choose the right components of the wind turbine to maximise performance.
(iv) To evaluate the economic situation of the design,
(v) To assess environmental and technical challenges.

2. METHODOLOGY

The monthly electricity consumption of the Highfield campus was constructed based on data obtained from the metering system [1].

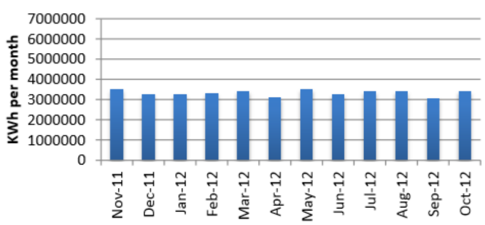

Figure 2. Electricity consumption of Highfield Campus per Month.

Based on the above-mentioned data, the total annual electricity consumption from 11/2011 to 11/2012 is 40040478 kWh, approximately 40GWh. The capacity of the generator can thus be determined as follows

Capacity = $\frac{40\ GWh \cdot 40\%}{8760h}$ = 1.826MW

However, about 10-20% of the total is added to the generator capacity in order to meet up with unusual peak load periods. The capacity can be approximated to 2MW.

- ***Site Selection***

In selecting a site to build and install the wind power plant, the first decision to be made is weather to install the plant offshore or onshore. After considering the economic, physical and social factors, a decision was made to install the wind plant offshore.

In selecting an ideal location to install the wind plant offshore, a number of steps was carried out.

Firstly, some possible sites on the map was chosen. 31 different places on the map are randomly chosen. These 31 points on the map are catalogued into three groups, marked as A1-A7, B1-B20 and C1-C4. The situation is shown in Figure 3.

Secondly, the data of the different wind speeds at the random points was collected. By using grid reference, the average wind speeds of these 31points are collected from the government official database [1]. Each point provides the estimated average value in one kilometre square area in terms of heights at 10 metres, 25 metres and 45 metres above the sea level respectively. There is no data available for point A5, thus A5 will not be considered in next step.


Figure 3. The chosen points on the map

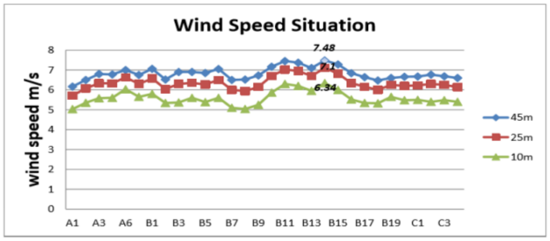

Figure 4. Average Wind Speed of the Chosen Points at different tower heights.

Looking at Figure 4, the wind speed at B14 is the highest of all chosen points, in terms of 10 meters, 25 meters and 45 meters tower height. Thus, B14 is chosen as the point to install the wind plant.

Also, points A1 and A2 are near the port of Southampton. If the wind power plant is constructed there, it might pose some disturbance to the transportation.

Furthermore, the points A3, A4, A5, A6 and A7 are distributed in residential areas. Installing the power plant in these areas would expose residents to noise (from the plant) and block some of their peripheral vison.

Another reason for choosing point B14 is that point B14 is near the Isle of Weight, which is a famous tourist destination. Constructing the wind power plant can be beneficial in promoting wind power as a viable renewable energy source. This was the reason that more points where selected around the Isle of Weight.

3. WIND POWER PLANT DESIGN

Earlier, point B14 was the chosen site for the wind plant installation based on data provided by the website in terms of 15m, 25m and 45m towers. However, as seen in Figure 4, better wind speeds are attained at higher heights. The wind shear equation gives a simple relation exist between height of tower and wind speed.

$$\mu = \mu_0 \bullet \left(\frac{z}{z_0}\right)^{\alpha} \qquad (1)$$

Where μ is the wind speed, z is the height, z_0 is the height in 10m, μ_0 is the wind speed at 10m, and α is Hellman's exponent. Where, α is the unknown parameter, it can be obtained from Table 2. Based on the table and the practical situation, α=0.1. The wind speeds for different heights was computed and is shown in figure 5.

Table 2. Value of α under different conditions

Location	α
Unstable air above open water surface	0.06
Neutral air above open water surface	0.10
Unstable air above flat open coast	0.11
Neutral air above flat open coast	0.16
Stable air above open water surface	0.27
Unstable air above human inhabited areas	0.27
Neutral air above human inhabited areas	0.34
Stable air above flat open coast	0.40
Stable air above human inhabited areas	0.60

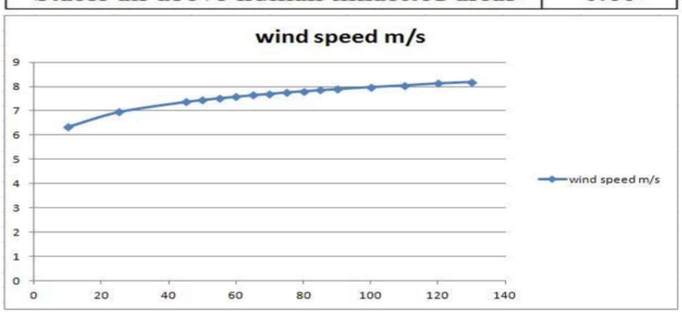

Figure 5. Relationship between wind speed and tower height.

The power output of the wind turbine is given by

$$P_{output} = \frac{\rho \bullet A \bullet V^3 \bullet C_p}{2}\eta \qquad (2)\ [3]$$

Where ρ is the air density at the chosen height when temperature is 15°C; A is the swept area of the turbine; V is the wind speed; C_p is the power coefficient and η is the efficiency of the wind turbine.

The efficiency is given as

$$\eta = \eta_{gear} \bullet \eta_{gen} \bullet \eta_{ele} \qquad (3)$$

Where η_{gear} is the gearbox efficiency, $\eta_{gen}$is the generator efficiency and$\eta_{ele}$is the electric efficiency. In this case,η_{gear}= 0.93, η_{gen} = 0.95 and η_{ele}= 0.90.
Therefore, η = 0.93 X 0.95 X 0.90 = 0.79515

- ***Length of blade and Tower Height***

Based on the equation (1) and (2), the relationship between length of blade (r) and towerheight (Z) is

$$R = \sqrt{\frac{2P}{\rho \bullet \pi \bullet C_p \bullet \eta \bullet U_0^3 \bullet \left(\frac{H}{H_0}\right)^{3a}}} \qquad (4)$$

Recall that the wind plant capacity was calculated to be 2MW. However, instead of constructing one unit of a 2MW wind plant, the design would combine two units of 1MW wind plant. This is done to reduce the complexity of the wind plant and also to increase the reliability of the plant. In the event that there is a fault on one of the turbines, the other could still be delivering power while the faulted turbine is fixed.
The tower height and the length of the blades is modelled under the MATLAB environment. The relationship between length of blade (R) and tower height (H) is shown in figure 6.

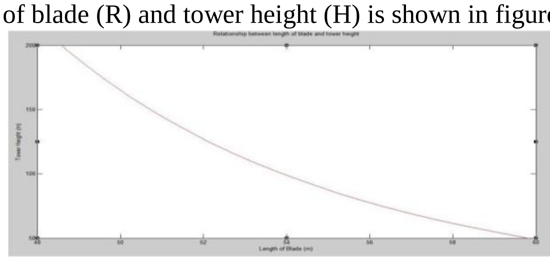

Figure 6. Relationship between length of blade (R) and tower height (H)
Also, since the height of tower should be between 2 or 3 times the length of blade, two lines, Z=2R and Z=3R are added to the basic R-H curve using MATLAB. The result is shown in Figure 7. As shown in Figure 7, point shared by H-R and H=3R is (50.6, 151.9) and point shared by H-R and H=2R is (53.3, 106.6). The choice is given in the middle value of these two points. Therefore, the length of the blade is 52m, and the relate tower height is 127m.

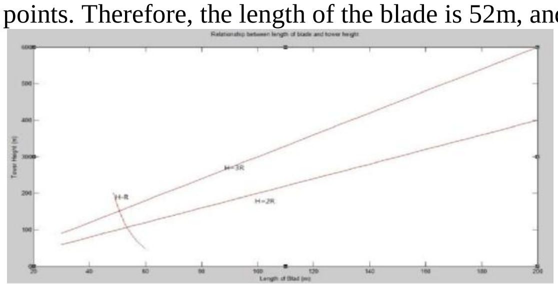

Figure 7. Selection of blade length and tower height.

- ***Rotor***

The rotor design is critical to the proper working of the wind turbine. The hub, the blade, the chord and angle of blade are the minimum requirements to be considered in designing the rotor.
The hub of the wind turbine is the component that connects the blades to the main shaft and ultimately to the rest of the drive train. The hub must withstand all the loads/forces generated by the blades. Hubs are typically made of steel or spheroidal graphite iron and they are protected externally by an oval enclosure. There are three basic types of hub design that have been utilized in modern wind turbines: Rigid hubs, teetering hubs, and hubs for hinged blades. Ref. [4] compared these three types of hub. The rigid hub would be used for this design as they are advantageous to turbines with three blades.
Another important element of a successful rotor design is the blade shape design, as well as the material being used. Blades are often made from light materials, such as fiber reinforced plastic materials, which have good resistance to wear and tear. Fibres made of glass or aluminum are generally for the blades of small and medium size wind turbines. Carbon fibersare used in the parts subject to more critical loads, and used for larger blades. This fiberconsists of polyester, epoxy resin or vinyl ester constituting two shells together and it has a good advantage by an internal matrix. The carbon fiber is selected to be the material of blades as it would offer robustness to the blades.
The chord and angle of blade require precise aerodynamic equipment for careful design. In this work, The FX66 shape is utilized as it one of the best airfoil profiles available as reported by [5]. The design is shown in Figure 8. The dimensions of each section and the corresponding shape is given.

	Root	2nd part	3rd part	4th part	5th part	6th part	Tip
Relative radius	0.125	0.271	0.417	0.563	0.709	0.855	1
Length of Chord	6.045[m]	3.126[m]	1.857[m]	1.44[m]	1.152[m]	0.968[m]	0.835[m]
Angle of blade	30.4[°]	26.18[°]	21.96[°]	17.74[°]	13.52[°]	9.3[°]	5.1[°]

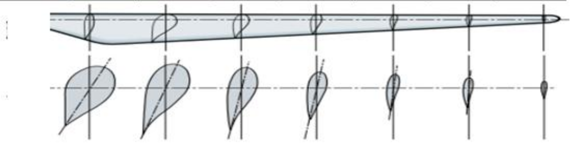

Figure 8. Blade design (Radius, chord length and angle)[5].

- ***Drivetrain***

Drivetrain is used to connect hub and generator, transmitting power from the rotating of the wind turbine to the AC generator. There are two types of drivetrain, one is the direct drivetrain, and the other one is the geared drivetrain. The main difference in the two types is the presence of a gearbox in a geared drivetrain to control the speed impressed on the shaft.

Depending on the gear box ratio, the geared drivetrain can divided into two types; The medium speed geared drivetrain (40:1) which usually use one gear stage and the high speed geared drivetrain (100:1) which uses two or four gear stages.

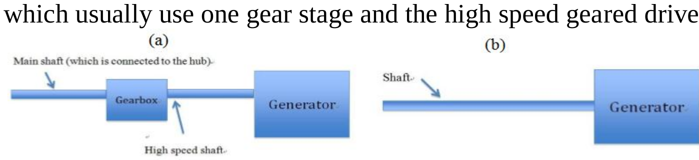

Figure 9. Basic structure of drivetrain. (a) Geared drivetrain and (b) direct drivetrain.

The capacity of the wind turbine is the main factor to be considered when making drivetrain selection.

Table 3. The capacity limitation for different types of drivetrains [6]

High speed geared drivetrain	1-6MW
Medium speed geared drivetrain	4MW-10MW
Direct drivetrain	2MW-6MW

As established earlier, the capacity of each of wind turbine is 1 MW. Considering table 3, the high speed geared drive train is selected for our wind turbine.

- ***Generator***

The doubly fed induction generator (DFIG) based on the adjustable speed generator (ASG) concept but with a four-quadrant ac-to-ac converter connected with the rotor windings(illustrated in Figure 10) is preferred in this design. This arrangement can be used to supply power at a fixed voltage and frequency when the rotor speed is not constant.

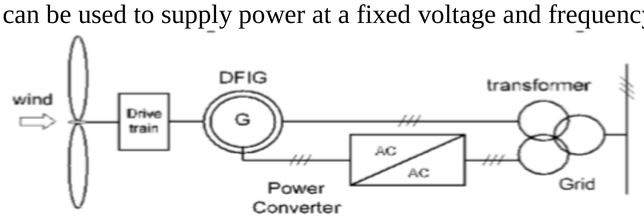

Figure 10. Variable speed wind turbine with doubly fed induction generator [7]

The DFIG also has the ability to extract the maximum energy from the wind for low wind speeds by optimising the turbine speed, as well as minimising mechanical stresses on the turbine when a gust of wind hits the turbine.

- ***Wind Turbine Control System***

The control system helps generate maximum energy from wind the minimum turbine load. Sources of load include turbulence, wind shear and tower shadow. Power output should be stable for all wind conditions to avoid overload.

The blade pitch control system is a system that controlled by hydraulics actuators and effectively turns the blade to get maximum advantage of the wind. However, if a burst of high wind speed suddenly, blades are controlled to turn so that the wind can go through it.

These systems may be designed mechanically or electrically. In the mechanical method, when there is a wind gust, the rotational speed of the rotor increases which generates a force on a regulating balancing weight which compresses a spring. In the electrical pitch control, its principle of operation is quite similar, but in this case, the spring is replaced by electrical operated controls. Electrical circuits may provide a direct link from the output of a sensor to the desired control action.

On a relatively large modern wind turbine like in the one designed to supply 40% of the power demand at the Highfield Campus of the University of Southampton, many sensors are used to communicate important aspects of turbine operation to the control system. These measured variables include speed (e.g. Wind speed), temperatures (e.g. Electronic temperatures), position (e.g. Blade pitch angle), electrical characteristics (e.g. Power factor and current), fluid flow parameters (e.g. Hydraulic pressures), environmental conditions (e.g. Lighting), motion, stresses and strain (e.g. Shaft torque).

In this design, the power operated controls are preferred because the automated electrical controls are more accurate and are easier to maintain compared to the mechanical method. An electronic sensor that is designed to sense the wind speed and sense the power output of the turbine is used. If the power goes beyond the safe level of operation of the turbine, higher or lower than normal level, an electronic signal is generated which pitches the blade out of the wind.

Other methods of control are passive stall control, active stall control and yaw power control. The passive control is effective but because a stall can produce strong vibrations, it could be detrimental to the structure of the blade. The active stall control is somewhat similar to the passive stall control, but after the nominal power has been achieved, it increases the angle of attack to reduce lift of the airfoil leading to a stall if nominal power is achieved [8]. The yaw control is not suitable for this turbine as they are usually used in turbines with smaller ratings, 1KW or less.

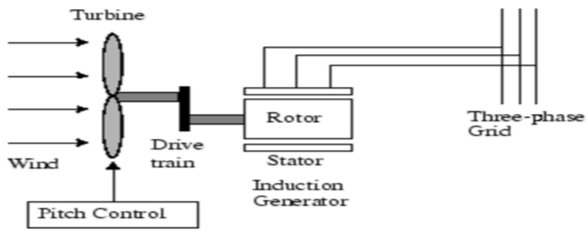

Figure 11. Blade pitch control system [9]

- ***Wind Turbine Foundation***

For offshore wind power plant, there are four types of foundation: monopile, jacket, tripile and gravity base as shown in Figure 12.

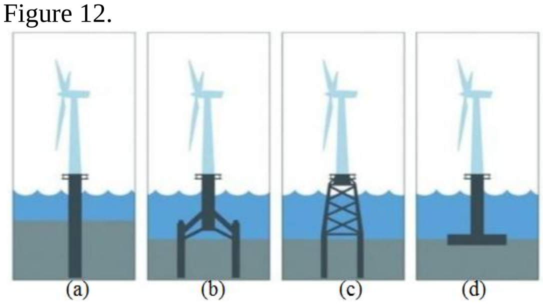

Figure 12. Wind turbine foundation. (a) monopile, (b) jacket, (c)tripile and (d) gravity base. [10]

The gravity base is chosen as the preferred foundation. The base is large, which reduce the pressure on the ground and still capable of holding the structure firmly to the ground. The other three types have areall driven into the seabed (32 to 64ft), they will cause acoustic emission and cause some disturbance to the surroundings which is a disadvantage as the site is around a tourist location. Furthermore, the gravity base is relatively cheaper than the other three types.

- ***Summary of design***

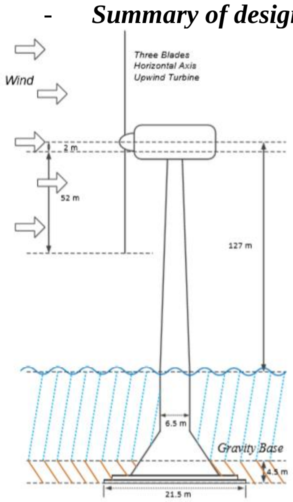

Figure 13. Module of the Designed Wind turbine. (Diameter of the tower is 6.5m to allow for lift installation for maintenance).

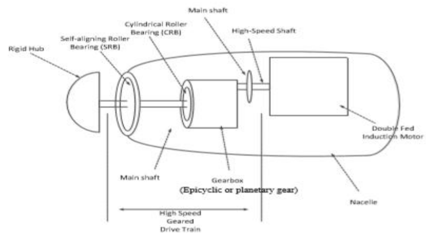

Figure 14. The Inner Component of the turbine.

4. DESIGN ANALYSIS

- ***Economic assessment of designed system***

The capital cost of offshore wind farm depends on many factors, such as turbine cost, grid connection cost, water depth, distance to shore, environmental conditions, soil type, etc. However this work is a conceptual design and a such some assumptions are made. To assume the turbine is located in the area where the distance to the shore is 10km long and the water depth is 30m. The capital cost (£/kW) should be:

Cost = Exchange rate * scale factor of depth * scale factor of distance * 1800………(5)

Where 1800 is the capital cost of wind power plant when it is set at 10 km away from shore and water depth is 10m. A scale factor of distance is 1.022 and the scale factor of depth is 1.237. The exchange rate is the rate between Euro and pound. Consequently, the expected capital cost is 1820 £/kW and the total capital cost is £3,640,000 for the 2MW wind plant.

In general, the O&M cost is 1.5% – 3% of the wind turbine costs (772 Euro/kW or 618 £/kW) annually. To assume the lifetime of the wind turbine is twenty years and cost proportion is 2.25%, the O&M cost should be 45% of the original turbine cost.

Thus, the O&M cost would be £556,200. Assuming that the availability of the system is 98%, the total investment can be calculated by the following equation.

Generating cost = (O&M cost +capital costs) ÷ Availability…………. (6)

Thus, the total investment is £4,281,836.74.

The payback time of the wind power system is given as;

$SP = C_C / AAR$………………. (7)

SP is the payback time, the C_C represents the total cost of the installation and the AAR is the annual average return. The AAR can be expressed by

$AAR = E_a P_e$…………..…. (8)

E_a is the amount of energy produced every year (kWh/year) and the P_e is the price obtained for the electricity (£/kWh) which is equal to the sum of the electricity price and the tariff.

Therefore, the payback period is

$SP = C_C / E_a P_e$……………….. (9)

For the wind power plant with total installed capacity is 2 MW, the tariff is 4.48p/Kwh in the period from 1st December 2012 to 31st March 2013 and the average price of the electricity in 2011 in the UK is 7.95p/Kwh[11]. So, the annual average return is

AAR = 2000kw * 8760h * (7.95 + 4.48) = 217, 773, 600p………… (10)

The total capital of the installation is 428,183,674p, so, the payback year is about

428,183,674/217,773,600=1.97 = 2 years (approx.)……….. (11)

- ***Environmental influence of plant.***

In the UK, the most common source for electricity production is from fossil fuel. For example, Southern Electric produces 22.3% electricity with coal, 55.0% with natural gas and 10.5% with nuclear, but only 9.7% with renewable source. The wind power plant would decrease emission of greenhouse gas due to the decreased fossil fuels use. Additionally, compared to the nuclear plant, no radiation will be produced.

In spite of this, the wind plant has some negative impact on environment. The site selection in this work is near the Isle of Wight where it is home to over 200 hundred species of birds. The installation of offshore wind farm inevitably affects flying birds. The negative effects include: (1) Collision with wind turbines can cause death of birds (2).Habitation loss of birds in the short-term, during construction of wind farms (3). Long term habitat loss, due to disturbances from boating activities connecting with maintenance (4). In terms of migration, wind farms act as barriers for birds which lead the increase of travelling distance. As a result, the birds may expel more energy during migration which can affect the lifespan of the birds (5) the disconnection of ecological units, such as the gap between roosting and feeding sites [12, 13].

5. CONCLUSION

This work aims to conceptually design a wind power plant that can provide 40% of the electric power demand of the Highfield Campus at the University of Southampton. After comparing onshore and offshore wind power, the offshore wind power plant is chosen. The capacity of the wind plant is 2MW. The location of the wind power plant is determined mainly based on the wind speed and the area around Isle of Wight was selected. The wind speeds should always be evaluated before embarking on a wind power project. The economic analysis showed that the investment made on the plant could be recovered in two years. Although this wind power plant can eliminate approximately 7.6MT CO_2 annually, it may affect the birds and aquatic life of the animals in the water especially during construction.

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