Small Scale Wind Powered Reverse Osmosis Plant without Batteries in Trinidad and Tobago

Rikhi Ramkissoon[#1], Krishpersad Manohar*[2], Anthony Ademola Adeyanju[#3]

[1]*Drilling Fluids Engineer, Baroid Trinidad Services Ltd., Port-of Spain, Trinidad, W.I.*
[2,3]*Lecturer, Mechanical and Manufacturing Engineering Department, The University of the West Indies,*
St. Augustine, Trinidad, W.I.

Abstract - *A wind-powered reverse osmosis desalination system was proposed in order to assess the potential of the development of renewable energy powered water desalination in Trinidad. A simulation model for the prediction of the power delivered for a given value of wind speed was adopted. Based on the average wind speed data (3.5 m/s) and salinity of the feed water, the amount of water that can be produced was calculated as 57.6 gal/day. The system had a modest 1 kW VAWT and shows potential to deliver fresh water throughout the year at 26.7 KWh/kgal operating from seawater with a salinity of 10,800 ppm.*

Keywords — *Vertical Axis wind turbine, Reverse Osmosis, Wind, Desalination.*

I. INTRODUCTION

Desalination of brackish or sea water represents an option that can alleviate water emergency that may arise. The high energy consumption can pose a major disadvantage of this solution. High cost and the negative environmental impacts also negatively affect this option. To offset the disadvantage, alternative sources of fuel can be looked at as a substitute to the traditional fuel sources. Renewable energy sources, such solar and wind energy, are viable options, especially for remote areas where there is no electrical power available. Fresh water availability especially in remote areas would benefit greatly by using the most readily available renewable energy (wind or solar), especially in stand-alone desalination operations. This separation process can be used for a wide variety of applications including desalination of sea water, treatment of industrial wastes, concentration of food products, and recovery of value materials from solution mixtures. [1]

The Desalination Company of Trinidad and Tobago Limited, (DesalcoTT) operates a desalination plant that intakes raw seawater from the Gulf of Paria, off Trinidad's west coast, cleanses it of its mineral content, and then sells the purified water to the island's Water and Sewerage Authority (WASA), the company's sole customer. The fresh water produced by the plant is 40 million gallons per day [2].

There are some examples of existing small-scale seawater desalination equipment that often requires a large and constant supply of energy, either electricity or diesel. Also preparing inexpensive membranes with specially adapted physicochemical characteristics may be a vital step in future chemical and waste treatment application [3]. If there is an availability of wind or solar energy in the desired location, this can be an attractive option if the supply of traditional fuels is either expensive or unreliable. Wind power technology is a feasible option for regions without electric power grid such as the rural communities in Trinidad and Tobago. In the east coast areas the average wind speed is 3 to 4 meters per second [4,5]. However, the worldwide numbers of installations that combine these technologies remain very small.

Most of the reverse osmosis desalination system powered by renewable energy incorporates the use of lead-acid battery banks. These batteries are charged via solar or wind powered devices and allow the reverse osmosis equipment to run continuously, which obviously maximizes the daily output for a given size of reverse osmosis plant. Desalination using reverse osmosis systems generally need a constant flow rates and pressure to realize the most efficient means of generating product. The use of the batteries allow this to occur. The major problem with lead acid batteries is that they experience a short life expectancy in hot climates, particularly in remote areas where they are often damaged easily and poorly maintained [6]. When designing reverse osmosis desalination systems which include a battery bank, the battery efficiency has to be considered. Even new batteries have significant energy loss in the charge/discharge cycle and, in a system that is powered via a renewable energy source, the design of the renewable energy device must take this into account. There is also a reduction of product water flow as the battery ages.

There are several small-scale demonstration wind powered reverse osmosis systems that are already running successfully [7]. The capital costs associated of these systems remain high, in comparison with reverse osmosis systems powered by grid electricity or diesel. A viable option is to build small scale reverse osmosis plants operating without batteries. Some experiences gathered worldwide with wind powered reverse osmosis plants without batteries were described in the literature [3, 8, 9]. There are several advantages of not using battery banks as a source for back-up power, mainly the capital cost significantly reduces as well as the maintenance needs. However, due to intermittent wind power supply and not using a battery bank, variable pressure and flow conditions are expected, adversely affecting the reverse osmosis membrane performance.

II. DESIGN PARAMETERS

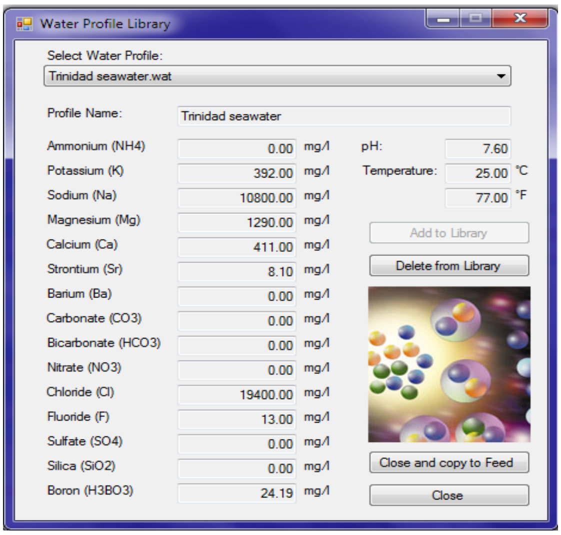
The use of renewable energy resources to a large extent is site specific and location dependent. The area under consideration in this work is the rural east coast of Trinidad to assess the potential of wind powered desalination as a viable alternate water source. A wind powered reverse osmosis desalination system is proposed, and a simulation model utilized to evaluate the amount of water produced based on the average wind speed data and salinity of the feed water.

A. Wind Energy

The wind speed data used was measured and recorded at the Piarco, Trinidad Meteorological Department, at ten meters above ground level, between 2010 and 2016. The tabulated results shown are the averaged value over seven years. Monthly files were obtained for each year, with the data recorded in four columns: month, day, hour, and hourly mean wind speed (Figure 1). The hourly mean wind speed was calculates as the average of the twelve pieces of data corresponding to the twelve periods of five minutes that make up each hour of original data.

B. Seawater in Trinidad and Tobago

In Trinidad, two main sources are available for desalination: the Caribbean Sea and the North Atlantic Ocean. The east coast of Trinidad is bounded by the Atlantic Ocean. The salinity of the water is around 3.6 % with water temperatures of between 32 to 36 degrees Celsius. Sodium chloride (NaCl) is the main component of salt in the water (10,800 mg/L), besides the cat-ions of Ca, Mg and the anions of SO_4 and HCO_3 that are considered to be scaling substances existing in relatively high concentrations as shown in Figure 2.



Select Water Profile: Trinidad seawater.wat

Profile Name: Trinidad seawater

Ammonium (NH4)	0.00	mg/l
Potassium (K)	392.00	mg/l
Sodium (Na)	10800.00	mg/l
Magnesium (Mg)	1290.00	mg/l
Calcium (Ca)	411.00	mg/l
Strontium (Sr)	8.10	mg/l
Barium (Ba)	0.00	mg/l
Carbonate (CO3)	0.00	mg/l
Bicarbonate (HCO3)	0.00	mg/l
Nitrate (NO3)	0.00	mg/l
Chloride (Cl)	19400.00	mg/l
Fluoride (F)	13.00	mg/l
Sulfate (SO4)	0.00	mg/l
Silica (SiO2)	0.00	mg/l
Boron (H3BO3)	24.19	mg/l

pH: 7.60

Temperature: 25.00 °C

77.00 °F

Fig. 2: Seawater profile for the North Atlantic Ocean.

C. Desalination in Trinidad using Wind Power

Presently in the Caribbean there are no small scale reverse osmosis water desalination plants using this renewable energy technology. However, the technology is available and there is easy access to the raw material (seawater) all around the islands. One of the main drawbacks towards moving in this direction is the high energy cost. This research explores the feasibility of using wind power as an alternative to fossil fuel as the driving agent for desalination process.

III. PLANT DESIGN AND OPERATIONAL PROCEDURES

	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec	*Avg*
2010	4.35	5.23	4.93	4.6	3.98	4.51	4.32	4	3.64	4.03	3.21	3.37	*4.18*
2011	4	3.82	4.12	5	3.8	3.96	3.47	3.45	3.86	3.32	3.43	4.53	*3.90*
2012	4.41	4.39	4.81	4.46	4.91	4.27	3.97	3.9	3.65	3.3	3.74	4	*4.15*
2013	3.1	3.9	4.2	4.1	3.6	3.8	2.4	1.8	1.7	2.1	2.2	2.8	*2.98*
2014	3.3	3.4	3.5	3.8	4	4.1	3.5	1.9	2.1	1.5	2.3	2.5	*2.99*
2015	3	3.1	3.5	3.8	4.6	4.2	3.1	2.3	2.2	2.5	2.5	3.1	*3.16*
2016	2.9	3.5	3.3	3.7	3.7	2.9	2.6	2.5					*3.14*

Fig. 1: Source: Met Office (2016): Trinidad Daily Wind Speed, Part of the Met Office data Archive, Met Office, Piarco, Trinidad.

A. Plant Design Methodology

Reverse osmosis wind powered plant with batteries normally designed for the battery capacity or the wind speed to define the operation strategies [8]. In systems where batteries are not employed, the wind speed will directly influences the load torque and, consequently, the permeate production. For wind powered reverse osmosis that does not utilize batteries the main parameter used to determine the pumped water volume over a period of time is the critical wind speed, which is the minimum wind velocity necessary to start the operation of the pumping system. The site mean wind speed determines this critical wind speed. The daily wind speed of the location that the reverse osmosis plant will be situated is very important in the designing of the plant and therefore, the size of the turbine.

B. Wind Turbine Selection

The wind turbine selected for this application was a Straight-Bladed Vertical Axis Wind Turbine (SB-VAWT). This design was selected because of its inherent advantages, mainly low cost and its ability to operate in wind from any direction without a yaw mechanism [10]. This particular VAWT used both lift as well as drag to generate power. It has the following characteristics:

- Maximum Power: 1 KW
- Rated Power: 750W
- Output Voltage: 12 V
- Output Current Max: 35 A
- Number of Blades: 3 Darrieus
- Rotor diameter: 6.76 m
- Speed Maximum power: 200 rpm
- Dimensions (W x H x D): 0.55 m x 3.07 m x 6.76 m

The Straight-Bladed VAWT was built and tested on the east coast at Manzanilla, Trinidad, approximately 50m from the coastline. The alternator charging currents were obtained from the performance output curve of these particular alternators used (Figure 3). An overall mechanical efficiency of 70% was estimated for the gearbox and mechanical linkages to convert the rotational energy of the turbine to electrical energy. The gearing system on the turbine enabled a setup ratio of 1:94 [11]. Using the experimental data for the model, the power delivered for a given value of wind speed was predicted.

C. Reverse Osmosis System

Reverse osmosis is a well-established technology for the desalination of water and in particular seawater. The use of reverse osmosis can be suitable in areas that are isolated and where a steady and reliable supply of electricity is a problem. The application of this technology, as applied as a stand-alone system, can be very useful.

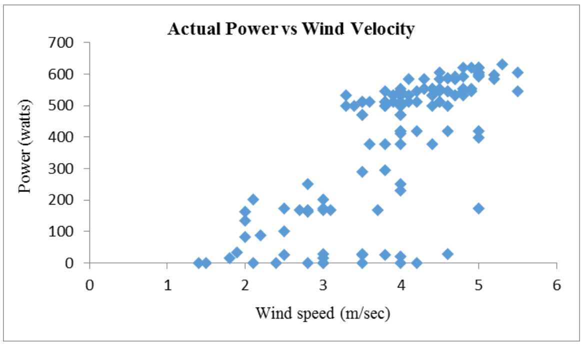


Fig. 3: VAWT power produced at Manzanilla, Trinidad.

The operational conditions that the plant has to be exposed to, is a determining factor in the membrane selection. High rejection rates and improved tolerance to pressure fluctuations has to be looked at in the type of membrane that has to be selected. It is believed that higher efficiencies can be obtained when operating at certain flow and pressure conditions. An important contribution dealing with variable flow and pressure operation of reverse osmosis membranes, which looks at the feasibility of wind-powered systems, was reported by Feron [12].

In this research, an operational window was established to determining the operational parameter variation to which a membrane can be safely submitted (Figure 4).

The four limits that define this window are:

a) Maximum feed pressure — determined by the membrane mechanical resistance;
b) Maximum brine flow rate — should not be exceeded to avoid membrane deterioration;
c) Minimum brine flow rate — it should be observed to avoid precipitation and consequent membrane fouling;
d) Maximum product concentration — if the applied pressure is less than a determined value, permeate concentration will be too high.

D. Membrane Selection

The seawater desalination membrane considered was the DOW FILMTEC SW30-2540 membrane. This membrane offers a variety of premium grade seawater reverse osmosis elements featuring both high active area and high salt rejection to offer long-term economics for seawater desalination systems (Table 1). SW30 seawater membrane elements have one of the highest flow rates available to meet the water demands of both sea-based and land-based desalinators. DOW FILMTEC SW30 membrane elements may also be

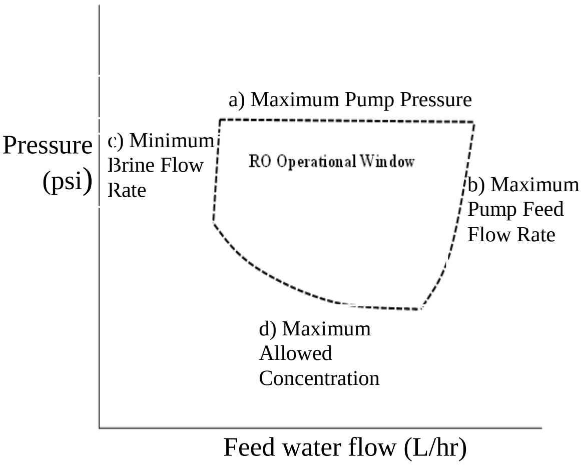


Fig. 4: Operational window for the RO membrane

operated at lower pressure to reduce pump size, cost, and operating expenses. DOW FILMTEC seawater membrane elements are more durable and may be cleaned more effectively over a wider pH range (1-13) than other RO elements.

TABLE 1:
SW30-2540 MEMBRANE CHARACTERISTICS
(SOURCE: DOW CHEMICAL COMPANY. 2017)

Applied Pressure (psig)	800
Permeate Flow Rate (gpd)	700
Stabilized Salt Rejection (%)	99.4

E. Wind Reverse Osmosis System

The simulated system was done based on experimental results from a (1 kW) vertical axis wind turbine. The unit was simulated as directly supplying a reverse osmosis desalination unit. The main components of the wind-powered reverse osmosis desalination system consist of the membrane separation section, which is fed via a high pressure reciprocating pump (pressurizing the feed stream up to the desirable pressure levels). The permeate stream leaving the membranes constitutes the lean product of the system. The high pressure pump operates by means of a three-phase motor where the electrical power is generated by the wind turbine. The pumping system is composed of two variable speed drives (inverter/induction motor) driving a medium and a high-pressure pump, each. The speed of each pump is individually controlled to maximize both wind power capture and product water flow.

IV. MODELING

For a VAWT of 1 KW capacity direct-coupled to the pump the main blocks for the simulations are: Vertical Axis Wind Turbine, DC motor-pumps (high and low pressure) and reverse osmosis membrane as shown in Figure 5.

For this VAWT, it generates power as a lift driven device. The power extracted is expressed as:

$$P = 0.5\rho V^3 C_L S \left[1 - \frac{\left(v/V_\infty\right) D}{L}\right] \frac{v}{V_\infty} \sqrt{1 + \left(\frac{v}{V_\infty}\right)^2}$$

where:

C_L represents the lift coefficient;
D represents the drag force;
L represents the lift force;
ρ Air density, in kg/m^3;
S Area of the surface described by the turbine rotor
perpendicular onto the wind direction, in m^2;
v Wind speed at the turbine blade, in m/s;
$V\infty$ Freestream velocity, in m/s.

The power generated by the wind turbine was modelled using equation (1), where the air density was considered as ρ=1.225 kg/m^3. Figure 5 shows the schematic layout of the plant in LABVIEW. The application input parameters are the nominal power of the wind turbine and the site's wind speed.

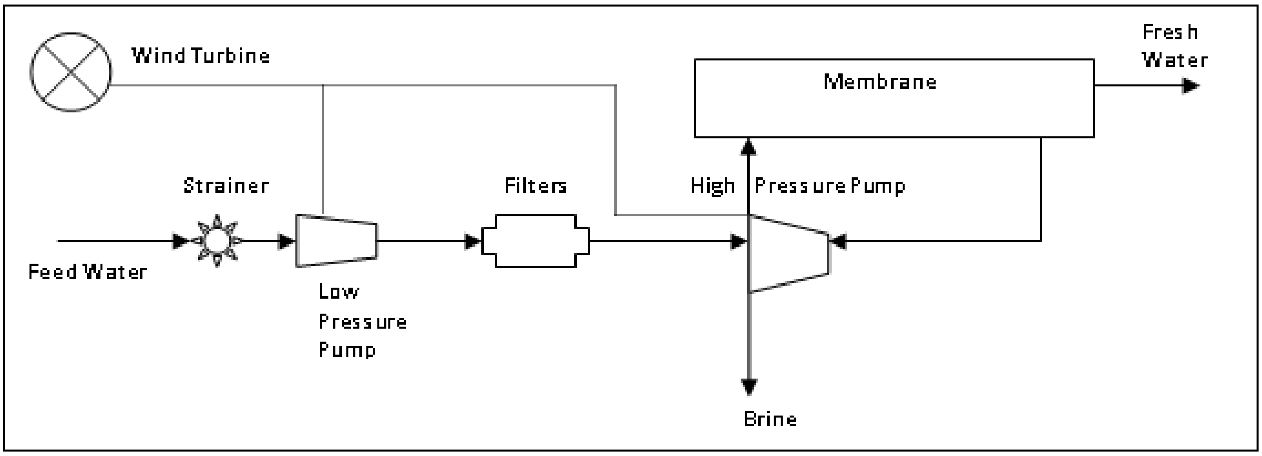


Figure 4: Layout of the Wind-powered Desalination Plant.

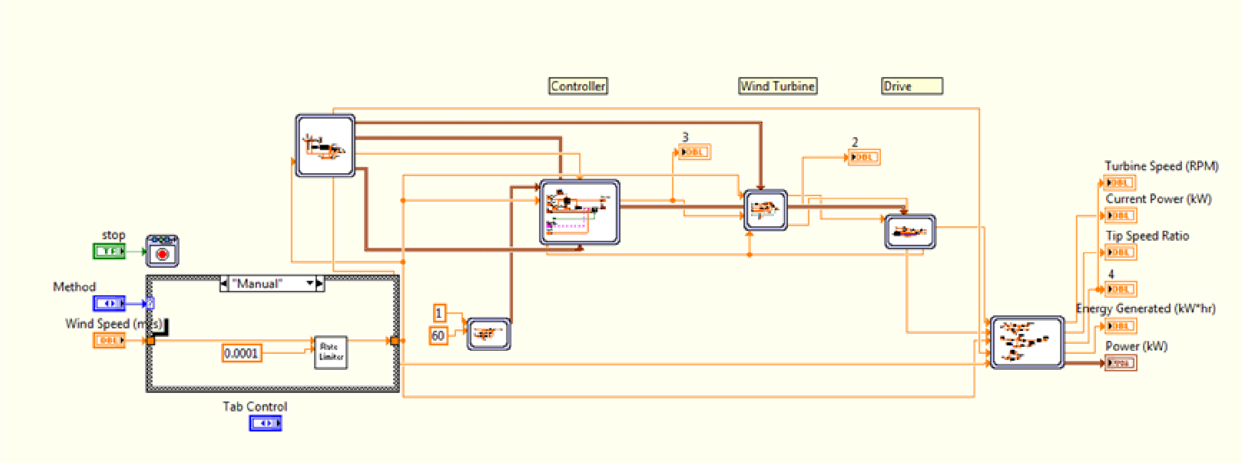


Fig. 5: LabView simulation for the

A. Pumps

The use of positive displacement pumps for desalination of seawater, especially for a high pressure feed, is commonly employed. A booster pump (centrifugal) is usually used to transfer the feed water from well/feed tank to the high pressure pump.

1) Plunger Pump

For this simulation the CAT 317 plunger pump with a triplex plunger action was selected. Pump speed, water flow rate, pump torque and pressure were used to model the pump performance. A Matlab polyfit function was used to model the variables of the pump and the results are illustrated in Figure 6.

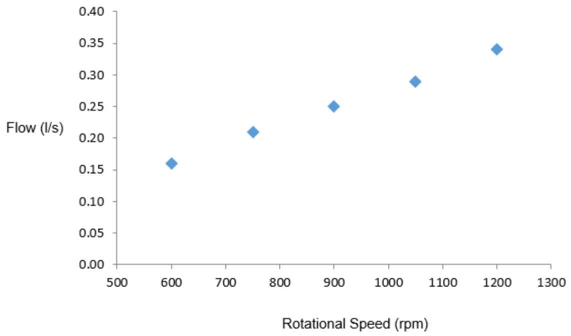


Fig. 6: Plunger pump flow as a function of the rotational speed.

The flow equation derived was:

$$Q_{PP}(w_{PP}\ \Delta P_{PP}) = k1_{QPP} + k2_{QPP}.\omega_{PP} + k3_{QPP}.\Delta P_{PP} + k4_{QPP}.\omega_{PP}.\Delta P_{PP}$$

The torque calculation equation derived was:

$$T(w_{PP}\ \Delta P_{PP}) = k1_{TPP} + k2_{TPP}.\Delta P_{PP} + k3_{TPP}.P_{PP}^2 + k4_{TPP}.\Delta P_{PP}^3 + k5_{TPP}.\omega_{PP} + k6_{TPP}.\omega_{PP}^2$$

Where:
Q_{PP} is the pluger pump output flow (l/s);
w_{PP} is the plunger pump rotational speed (rpm);
T_{PP} is the plunger pump shaft torque (N.m);
ΔP_{PP} is the plunger pump differential pressure;
ki_{QPP} are the coefficients of yhe outlet flow function;
ki_{TPP} are the constants of the shaft torque function;

2) Moineau Pump

The centrifugal pump was modelled as the primary pumping device for conveying feed pressure. The Moineau pump is a 'screw-type' pump in which the pumping action is achieved by turning the rotor eccentrically within the stator. The pump modelling was similar to the plunger pump (Figure 7).

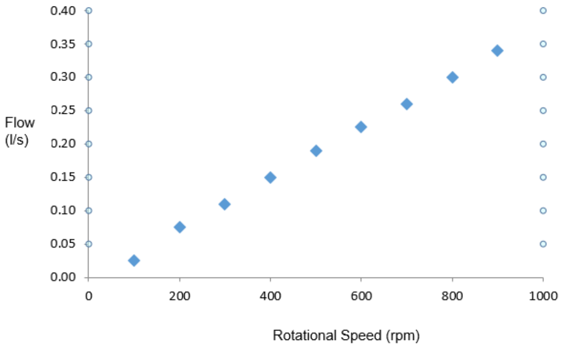


Fig. 7: Moineau pump flow as a function of the rotational speeds.

The flow equation derived was:

$$Q_{MP}(w_{MP}\ \Delta P_{MP}) = k1_{QMP} + k2_{QMP}.\omega_{PP} + k3_{QMP}.\omega_{MP}^2 + k4_{QMP}.\Delta P_{MP}$$

The torque calculation equation derived was:

$$T_{MP}(w_{MP}\ \Delta P_{MP}) = k1_{TMP} + k2_{TMP}.\Delta P_{MP} + k3_{TMP}.P_{MP}^2 + k4_{TMP}.\omega_{MP} + k5_{TMP}.\omega_{MP}^2 + k6_{TMP}.\omega_{MP}^3 + k7_{TMP}.\omega_{MP}^4$$

Where,
Q_{MP} is the Moineau pump output flow (l/s);
w_{MP} is the Moineau pump rotational speed (rpm);
T_{MP} is the Moineau pump shaft torque (N.m);
ΔP_{MP} is the Moineau pump differential pressure;
ki_{QMP} are the coefficients of yhe outlet flow function;
ki_{TMP} are the constants of the shaft torque function;

B. DC Motor-Pump Block

The behaviour of the permanent magnet DC motor is described by the equations:

$$T_e = K_m I_{PV}$$

$$K_m = (V_m - R_a I_{PV})/\omega$$

$$\frac{d\omega}{dt} = (T_e - T_f - T_{load})/J$$

where R_a is the armature resistance, ω is the angular speed, K_m is a motor constant, T_e, T_f , T_{LOAD} are the electrical, no load and load torque and J is the total inertia. The motor is coupled to the pump via the load torque, T_{LOAD}. In these reverse osmosis applications high pump pressures are required. The diaphragm pump can provide the required high pressures therefore it is a promising alternative in small-scale installations. In this kind of pump has the water flow (Q_1) is proportional to angular speed, or:

$$Q_1 = k_1 \omega$$

where k_1 is a constant. As the simulation step size is very small compared to the pressure variation, the head can be considered constant. The pump pressure, P_1, is therefore given by:

$$\boldsymbol{P_1 = k_2 V_M I_M / Q_1}$$

where k_2 is a constant. It was noticed that when the simulation was done, the mean current used was adequate, although 3-diaphragm pump causes a current oscillation of about 40%, due to the controller working at 50 kHz and the oscillation is around 360.5 Hz . The design was simulated using the ROSA software.

V. PERFORMANCE ANALYSIS

Using the vertical axis wind turbine model, the power delivered for a given value of wind speed was predicted. This model was based on theoretical modelling of the individual component characterization, supplemented by manufacture's data. The salinity of the seawater feed was taken to reflect that of the North Atlantic at 10,800 ppm. Additionally, the feed temperature was assumed constant at 25°C.

A. Long-Term (Steady-State) Performance

This analysis was carried out to establish the input-output characteristic of the system, i.e. the relationship between wind-speed and fresh water production, as depicted in Figure 8.

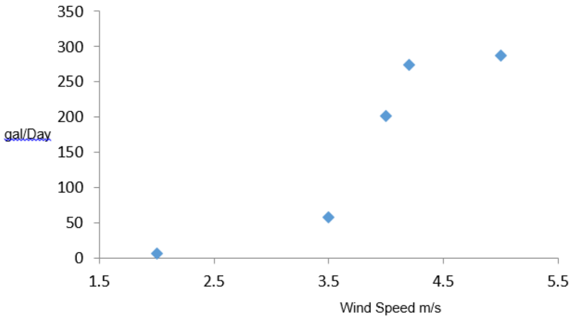


Fig. 8: Wind speed vs. Fresh water production.

This relationship between the wind speed and fresh water produced can be used in a system site study. Similarly to a wind turbine power curve, it would give the expected output from the system, given the resource in a certain location. The result is the water production probability expected for this location. The average wind speed recorded at Piarco was 3.5 m/s over the years 2010 to 2016 which when modelled gave 57.6 gal/day (21,024 gal/year) fresh water produced. Figure 9 shows the system specific energy as a function of the wind speed.

It presents an overall value below 26.7 kWh/kgal, being slightly higher at lower wind speeds. Nevertheless, it is almost constant throughout the operating range. This translates in the fact that water production was directly related to the available power.

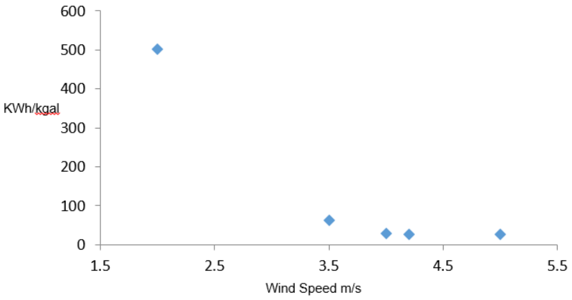


Fig. 9: System specific energy as a function of the wind speed.

VI. CONCLUSIONS

This work presented the analysis of a small wind-powered reverse osmosis desalination system. One of the main objectives of this analysis was to verify the integration of the several components, which were individually tested and modelled, and their performance over a wide operational range. More important was to demonstrate the proposed configuration as a promising alternative for the desalination of seawater. A more representative validation of the system will be only possible after prototype testing.

Prototype testing will provide a deeper understanding of the system performance, particularly considering the transients present in a system supplied by an extremely variable and unpredictable source, such as wind power. A high-efficiency configuration can be used, having a Clark pump as the concentrate stream hydraulic energy recovery device to improve the desalination system.

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