Potential of Wind-Powered Renewable Energy Membrane Systems for Ghana

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Abstract: Areas of the world that lack fresh water often have an ample supply of wind or solar energy, making renewable energy an attractive option as a power source for desalination systems. Particularly, wind energy is attractive because of its relatively low cost, high efficiency, and recent technological advancements in this area of research. To open system applicability to a broader range of geographical areas, the feasibility of substituting solar panels with a wind turbine on an existing membrane desalination system that has undergone testing in the Australian outback is examined. The use of wind turbines will provide greater scope for the system’s implementation in various parts of the world according to the local wind or solar resources. A comparison of several small wind turbines coupled with wind speed data from Ghana showed that a 1kW FuturEnergy wind turbine would give the best performance for the lowest cost and is therefore the most appropriate for coupling with the membrane system. The predicted permeate flowrate is 1.3 m³/day at a specific energy consumption (SEC) of 1.8 kWh/m³.

Keywords: Brackish water; Ghana; Membranes; Reverse osmosis; Wind power

Introduction

As a result of the worldwide water crisis, the United Nations declared the years 2005 to 2015 the International Decade for Action ‘Water for Life’ [1]. The primary goal of this effort is to fulfil the international commitments regarding water and related issues by 2015. This includes the Millennium Development Goals (MDG) which are to reduce by half the proportion of people with sustainable access to drinking water and stop the unsustainable exploitation of water resources [2]. A survey by the World Health Organization and UNICEF in 2002 showed that the MDG for safe drinking water should be achieved in most areas of the world with the exception of sub-Saharan Africa [3]. The fact that an estimated 420,000 people die every week from diseases related to unsafe drinking water and inadequate sanitation means that there is a need for an economical means of purifying the available water sources in order to prevent the spread of waterborne diseases.

The use of renewable energy driven reverse osmosis (RO) membrane filtration systems can be a viable alternative to other methods of filtration, especially for remote communities with potable water and energy supplies. The fact that renewable energy sources generate an intermittent supply of power creates many challenges when trying to match them to the water requirements of a small community. The use of wind power is particularly attractive because of the relative maturity of the technology associated with this resource and the fact that it allows greater flexibility of the existing solar powered system. The existing renewable energy membrane system is designed to desalinate water from brackish sources and has undergone testing in the Australian outback [4, 5]. The use of wind turbines will provide greater flexibility for implementing the RO membrane system in various locations around the world.

There have been several studies performed on the use of wind turbines to power membrane filtration units ranging from small (<10 m³/day) [6-12] to large-scale (>100 m³/day) [13, 14]. Most of them are either mechanically driven systems using multi-vaned windmills or electrically driven systems using small scale wind turbines. Both systems require the output from the wind turbine to drive a pump in order to raise the pressure of the feedwater so that it can pass through the membrane filtration system. The required pressure of the feedwater is linked closely to the performance of the system and the quality of the feedwater. Table 1 demonstrates how RO systems designed for seawater desalination (35 g/L) require an operating pressure of up to ten times that of systems designed for brackish water desalination (1-10 g/L). This paper deals with the implementation of small scale wind-powered systems, examples of which are shown in Table 1.

One of the most important criteria for determining the feasibility of these systems is the specific energy consumption (SEC, unit: kWh/m³), as this ultimately determines the cost of the system. This is due to the fact that the SEC demonstrates the water productivity and power consumption, which translates into the required wind turbine output and membrane surface area and hence capital investment. Recovery describes the amount of clean water (permeate) that is produced compared to the feed flow. In the case of brackish desalination systems, low recoveries (10-25%) are sometimes used to reduce fouling of the RO membrane and to avoid the generation of a highly concentrated waste brine. This means that four to ten times as much feed water compared to permeate must be pumped through the system for any given output, although this water may be suitable for non-potable purposes in the case of brackish water applications [15].

Table 1. Overview of small scale wind-powered membrane filtration units (brackish and seawater).

<table>
<thead>
<tr>
<th>Location</th>
<th>TDS (g/L)</th>
<th>Pressure (bar)</th>
<th>Salt Retention (%)</th>
<th>Recovery (%)</th>
<th>Permeate (m³/d)</th>
<th>Wind Turbine (kW)</th>
<th>Energy Storage kWh</th>
<th>SEC kWh/m³</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>UK</td>
<td>40</td>
<td>40-60</td>
<td>97*</td>
<td>30-45*</td>
<td>8.5*</td>
<td>2.2</td>
<td>None</td>
<td>3.4*</td>
<td>[6]</td>
</tr>
<tr>
<td>Germany</td>
<td>36</td>
<td>80</td>
<td>27*</td>
<td>6</td>
<td>0.9</td>
<td>Battery</td>
<td>11</td>
<td></td>
<td>[12]</td>
</tr>
<tr>
<td>Colombia</td>
<td>35</td>
<td>3.4-5.5</td>
<td>99</td>
<td>3.0-9.7</td>
<td>0.4</td>
<td>None</td>
<td></td>
<td></td>
<td>[11]</td>
</tr>
<tr>
<td>Hawaii</td>
<td>3</td>
<td>5.2-7.2</td>
<td>97</td>
<td>20</td>
<td>4</td>
<td>Pressure stabilizer</td>
<td>1.1*</td>
<td></td>
<td>[10]</td>
</tr>
<tr>
<td>Australia</td>
<td>2-6</td>
<td>6-11</td>
<td>83</td>
<td>9.3</td>
<td>0.21</td>
<td>&lt; 0.15</td>
<td>Pressure vessel</td>
<td>0.7*</td>
<td>[9]</td>
</tr>
<tr>
<td>Greece</td>
<td>36</td>
<td>58</td>
<td>99*</td>
<td>15</td>
<td>0.6-1</td>
<td>Battery</td>
<td>16.9*</td>
<td></td>
<td>[8]</td>
</tr>
</tbody>
</table>

*Calculated by current authors
†Simulated results

A variable flow RO seawater desalination unit (UK) powered by a 2.2 kW wind turbine underwent preliminary testing at the Centre for Renewable Energy Systems Technology (CREST) at Loughborough University [6, 15]. The system had no battery storage, so that the instantaneous power created had to be matched with the membrane system. The predicted permeate flowrate is 1.3 m³/day at a specific energy consumption (SEC) of 1.8 kWh/m³.

Considerable when the system was restarted and the permeate concentration would overshoot to high values before returning to normal. This was attributed to natural osmosis occurring at levels below the osmotic pressure and indicates the importance of keeping adequate pressure or flowrate in order to the feed water flowing to avoid spikes in permeate concentration [15]. It is also important to have an adequate electronic control mechanism in order to reduce the likelihood of surges in pressure and flow and therefore avoid damage to the RO membrane. The net present value of the system was calculated to be £51,000 with an estimated cost of water of 0.80€/m³ based on a system lifetime of 20 years.

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**Table 1.** Overview of small scale wind-powered membrane filtration units (brackish and seawater).

- **Location:** Various geographical areas
- **TDS (g/L):** Various concentrations
- **Pressure (bar):** Range of operational pressures
- **Salt Retention (%):** Efficiency of salt rejection
- **Recovery (%):** Percentage of clean water produced
- **Permeate (m³/d):** Predicted permeate flowrate
- **Wind Turbine (kW):** Rated power of wind turbines
- **Energy Storage kWh:** Energy storage capacity
- **SEC kWh/m³:** Specific energy consumption

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**References:**

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11. doi:10.1016/j.desal.2008.05.053
13. doi:10.1016/j.desal.2008.05.053
15. doi:10.1016/j.desal.2008.05.053
An example of a multi-vaned windmill driven design is the prototype system on Coconut Island off the coast of Hawaii, where the windmill is used to mechanically drive a pump in order to raise the pressure of the feedwater for RO desalination [10]. A feedback control mechanism was developed that enabled the system to be operated satisfactorily under mild ambient wind speeds of 5 m/s or less. A flow/pressure stabilizer was used in order to regulate the pressure and flowrate to the RO system thereby increasing the system efficiency. The RO system could process 13 L/min of brackish water with an average rejection rate of 97% and recovery ratio of 20%. This study showed that in general, the energy efficiency of the system decreased as the wind speed increased. The system was found to have an average energy efficiency of 35%.

A rotary-vane windmill was also used as the power source for a RO desalination unit in Australia [9]. The low-pressure system was designed for brackish water desalination and tested over a period of 13 months. The system freshwater production was 150-300 L/d at an average wind speed of 3 m/s. Recoveries ranged from 6.2-11.9% whilst the salt rejection averaged 83%. The system included a pressure vessel to store feedwater under pressure to keep flow and pressure at an acceptable rate, and a small diesel or portable gasoline pump was used during periods of low energy input and high demand. It was found that below wind speeds of 4.5 m/s, the system relied on the stored energy in the pressure vessel. A cost comparison showed that wind-powered RO is economically viable in comparison to similar technologies at production rates of 500 L/d or more. However, a cost analysis showed that it was still more economical to cart water around 30-40 km than to desalinate using RO technologies and pumping using diesel equipment.

With all of the systems studied, the actual cost of fresh water due to the life cycle cost (cost of the system over its entire life span; generally taken as 20 years) of the RO system becomes one of the most important factors influencing its wide scale implementation. An economic analysis of wind-powered desalination showed that the main factors influencing the cost of fresh water for a wind-powered RO plan are plant capacity, specific energy consumption, operation and maintenance of the RO plant, average wind speed and the real discount rate (the difference between the cost of water for a wind-powered RO plant and a conventional energy driven one) [13]. A cost analysis of a RO desalination unit powered by wind turbines and photovoltaics using a theoretical model showed that the PV system has the highest proportion of the annual system cost (27%), due to its high capital cost [8]. The study also showed that it is much more cost-effective to store fresh water as opposed to electrical energy, demonstrated by the cost of storing water in a tank (1%) compared to the electrical energy storage in batteries (12%). The health implications associated with storing fresh water are an issue that must be taken into consideration in designing these systems combined with the advantage of increased security of water availability due to water storage.

For wind powered desalination, wind speed has a direct effect on the running cost of a system, as it determines system productivity. An analytical study on using wind power (>50kW) for reverse osmosis seawater desalination was undertaken at their design by determining the economic and site characteristics [14]. The results indicated that the unit cost of water produced by desalination can be reduced by up to 20% for regions with a mean wind velocity higher than 5 m/s.

**Reverse Osmosis Membrane System**

The objective of this study is to look at the feasibility of replacing the solar panels on an existing membrane desalination system with a wind turbine. The use of wind turbines could provide increased performance and significant cost savings for system implementation in areas with a good wind resource. All of the systems are mounted on an off-road trailer to respect to the membrane, and the type of turbine according to the energy required and the site characteristics [14]. The results indicated that the unit cost of water produced by desalination can be reduced by up to 20% for regions with a mean wind velocity higher than 5 m/s.

**Wind Resource in Ghana**

The SWERA (Solar and Wind Energy Resource Assessment) programme began in Ghana in August 2002 as part of a global project to supply high quality renewable energy resource information [22]. The assessment of the wind resource covered the whole of Ghana with the primary focus being on the potential for large-scale grid connected wind turbines. The collection of dependable data on the wind resource in Ghana only began in 1999 when the Energy Commission started taking measurements at 11 coastal sites East and West of the Meridian (around Accra). The monthly average wind speed at 12 m is 4.8–5.5 m/s, which shows that Ghana has an adequate wind resource for power generation, as average wind speeds of greater than 4m/s are generally considered to have generation potential.

As part of the SWERA project the National Renewable Energy Laboratory (NREL, USA) developed high-resolution (1 km²) wind energy resource maps for Ghana [24]. The mapping system used by NREL is a combination of analytical, numerical and empirical methods using Geographic Information System (GIS) mapping tools. The best surface data for the wind assessment was obtained from the measurement stations along the coastline mentioned above, whilst the rest was computed from satellite ocean wave measurements. The resulting wind energy resource map shows that there is a Class 2 (6.2 – 7.1 m/s) wind resource at a height of 50 metres along the coast in southeast Ghana, around Accra [25]. There is a good to excellent Class 5 (8.4 – 9.0 m/s) wind resource in the higher regions northwest of Accra and along the border with Togo. The studies showed that the total land area with a Class 3 wind resource or higher is 1128 km², which represents about 0.5% of Ghana’s total area.

In order to investigate the potential performance of the membrane system in Ghana, average monthly wind speed data was used from a previously published study [26]. The average monthly values were based on the average daily mean value at a height of 2 m above the ground from readings taken close to Accra. The log law was used in order to give the wind speeds at a height of 8 m, which is a more realistic hub height for a wind turbine mounted on top of the trailer for the membrane system. **Figure 1** shows the variation in the average monthly wind speed in Accra at a...
height of 8 m. The average wind speed is 4.3 m/s over a range from 3.8 – 5.4 m/s. The wind speed characteristics are better analysed using the Weibull distribution, which calculates the probability that the wind speed will exceed a certain value [27]. A Weibull shape factor of 3 was used, as this is typical of areas which experience the trade winds. The Weibull distribution for Accra (Figure 2) shows how the higher shape value factor means that the curve has a sharp peak, indicating less wind speed variation. In general, the average wind speed data for Accra shows an adequate wind speed velocity with little variation, which is well suited to wind energy production.

Small Wind Turbine Comparison

The Weibull distribution and wind turbine power curves were used to compare eight different wind turbines that are currently marketed in the UK. This allowed the calculation of the annual energy production of the wind turbines based on the wind data for Accra, which provides a good basis for determining the most feasible wind turbine for this particular situation. Figure 3 shows the total annual energy production and the capacity factor for each of the eight wind turbines. The capacity factor is the ratio of energy generated over the year to the energy that the wind turbine would produce at its rated power over the same time period. The Proven Energy wind turbine has the highest capacity factor giving a good indication of how efficiently it would operate in the given wind conditions. The Swift wind turbine produces up to twice the amount of energy of some of the other designs, and initially this seemed to be an obvious result due to a higher rated output of 1.5 kW compared to power ratings of 1.1 kW or less for the other models. Further analysis of the performances of the wind turbines (Table 2) is required in order to make an accurate comparison.

Figure 3. Comparison of calculated annual energy production and capacity factor (Accra, 1991).

The comparison of wind turbine performance shown in Table 2 highlights the differences in their annual energy output with respect to their operating characteristics. When the wind turbine hub height is increased from 4 to 8 m, the energy output approximately doubles for each of the turbines for this particular location and conditions. At lower average wind speeds, it becomes apparent that the cut-in wind speed (when the turbine starts to generate power) and the initial steepness of the power curve have a large effect on energy output. This is highlighted by the fact that although the MiniWind wind turbine is rated at 1.1 kW, it has a high cut-in speed (3.8 m/s) and a relatively shallow power curve and therefore has a similar energy production to the Ampair 600 W wind turbine. It must be noted that this performance comparison is unique for this situation where the average annual wind speed is relatively low for wind energy production.

Table 2. Comparison of several small wind turbines available in the UK, rated at 1.5kW or less. [28]

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Rated Power (kW)</th>
<th>Rated Speed (m/s)</th>
<th>Cut-in Wind Speed (m/s)</th>
<th>Blade Diameter (m)</th>
<th>Generator Output (VDC)</th>
<th>Approx. Cost (£k)</th>
<th>Capacity Factor 4m (%)</th>
<th>Annual Energy Output: Accra (kWh) 4m 8m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airdolphin</td>
<td>1.00</td>
<td>12.5</td>
<td>2.5</td>
<td>1.0</td>
<td>25</td>
<td>6.5</td>
<td>5</td>
<td>425 710</td>
</tr>
<tr>
<td>Ampair</td>
<td>0.60</td>
<td>11.0</td>
<td>3.0</td>
<td>1.7</td>
<td>48</td>
<td>2.9</td>
<td>7</td>
<td>389 580</td>
</tr>
<tr>
<td>Fortis</td>
<td>0.80</td>
<td>14.0</td>
<td>3.0</td>
<td>2.2</td>
<td>24</td>
<td>1.5</td>
<td>5</td>
<td>320 590</td>
</tr>
<tr>
<td>FuturEnergy</td>
<td>1.00</td>
<td>12.5</td>
<td>3.2</td>
<td>1.8</td>
<td>48</td>
<td>0.7</td>
<td>6</td>
<td>490 830</td>
</tr>
<tr>
<td>MiniWind</td>
<td>1.10</td>
<td>12.0</td>
<td>3.8</td>
<td>1.8</td>
<td>48</td>
<td>0.8</td>
<td>4</td>
<td>343 580</td>
</tr>
<tr>
<td>Proven Energy</td>
<td>0.60</td>
<td>12.0</td>
<td>2.5</td>
<td>2.6</td>
<td>48</td>
<td>2.9</td>
<td>10</td>
<td>531 810</td>
</tr>
<tr>
<td>Ropatec</td>
<td>0.75</td>
<td>14.0</td>
<td>2.0</td>
<td>1.5</td>
<td>48</td>
<td>2.8</td>
<td>3</td>
<td>207 340</td>
</tr>
<tr>
<td>Swift</td>
<td>1.50</td>
<td>12.0</td>
<td>2.3</td>
<td>2.1</td>
<td>240*</td>
<td>6.2</td>
<td>6</td>
<td>836 1250</td>
</tr>
</tbody>
</table>

*Voltage is VAC
Discussion of Results

In order to get some indication of the predicted performance of the membrane system coupled to a wind turbine, the quantity of fresh water that can be produced is a simple calculation. For this purpose, a SEC of 1.8 kWh/m³ is used which is representative of a BW30 membrane operating with brackish feed water (TDS 8290 µS/cm) at 11 bar and 400 L/h [4]. Using this SEC and the annual power output of the FuturEnergy 1kW wind turbine operating in Accra, the membrane system could theoretically produce about 1.3 m³/day (assuming all of the produced energy could be used and the specific energy consumption did not vary significantly). This would be a sufficient supply of clean water to provide a small community of about 50-100 people. When comparing the wind turbines that were analysed the Proven Energy wind turbine appeared to have the best overall performance, but when cost is taken into consideration it quickly becomes apparent that the 1kW FuturEnergy wind turbine is the most economical and efficient wind turbine for this specific application. Further analysis of detailed wind data and the performance characteristics of the membrane filtration system through pilot tests are required before an accurate judgment of the system performance in this particular location can be made.

Conclusions

There is a need for further research into the area of brackish water desalination by small scale wind-powered membrane systems. Most of the research done in this area has been directed at larger scale systems (for example Enercon systems, which produce >175 m³/day [29]) and does not have the same implications on a smaller scale. The results of these wind turbine analyses show that a wind-powered membrane system would provide a sufficient quantity and quality of water, depending on the average wind speed. For this particular system, initial research shows that an average wind speed of >4 m/s seems to be adequate. Testing of the prototype membrane system required is to investigate the effects of transient operation on the permeate flow rate and purity, especially considering the variability of an energy source like the wind.

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References


