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POTENTIALS OF WIND ENERGY DEVELOPMENT FOR WATER DESALINATION IN JORDAN

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SUMMARY

The potential of the development of water desalination using wind energy in Jordan was studied. Eleven wind solar sites were considered. The results show that these sites can be divided, in terms of the yearly total amount of desalinated water, into three categories. One is considered favourable, which includes Ras Muneef, Mafraq, and Aqaba. Their water production adds up to about 75% of all water produced from all 11 sites combined. Others are considered to be promising (about 24% in total), which include H-5, Irbid, and Ma'an. The rest of sites considered are found to be very poor, which include H-4, Amman, Queen Alia Airport, Shoubak, and Deiralla, with traces of water produced (less than 1%).

KEY WORDS wind power; reverse osmosis desalination

1. INTRODUCTION

In Jordan, municipal, industrial, and agricultural water demand is continuously increasing due to rapid population growth and consumption. According to Murakami (1995), by the year 2000, water withdrawals in Jordan will exceed its total freshwater potential. By then, Jordan would have depleted virtually all of its renewable sources of fresh water. Furthermore, the gap between supply and demand is increasing. In order to increase the non-conventional water resources in Jordan as supplements to conventional water supply, there are few methods that can be considered; first, imported water. Secondly, desalination of sea water at the Gulf of Aqaba, as well as the desalination of brackish water where it can be available in different locations of the country. Water reuse and reclamation, rain water harvesting and cloud seeding can also be considered. Each one of these methods has its energy requirements.

In addition to shortage of fresh water resources, Jordan is suffering from shortages in conventional energy sources such as petroleum and natural gas. The limited energy sources in Jordan makes considering renewable energy options such as solar, wind, and hydropower very attractive. In this paper, the potential of the development of water desalination using wind energy in Jordan is going to be discussed. It has been shown that wind energy is an appropriate method for reverse osmosis (RO) desalination (Feron, 1985; Warfel *et al*., 1988), its energy consumption is about 8 to 12 $\mathrm{kW\,h\,m^{-3}}$ of fresh water. The minimum energy requirement varies more or less proportionally to the salt concentration.

2. WIND ENERGY IN JORDAN

It is very well established that wind-energy resource is large and globally wide spread. For different applications in many locations, it is clear that wind energy can be competitive (Musgrove, 1987;

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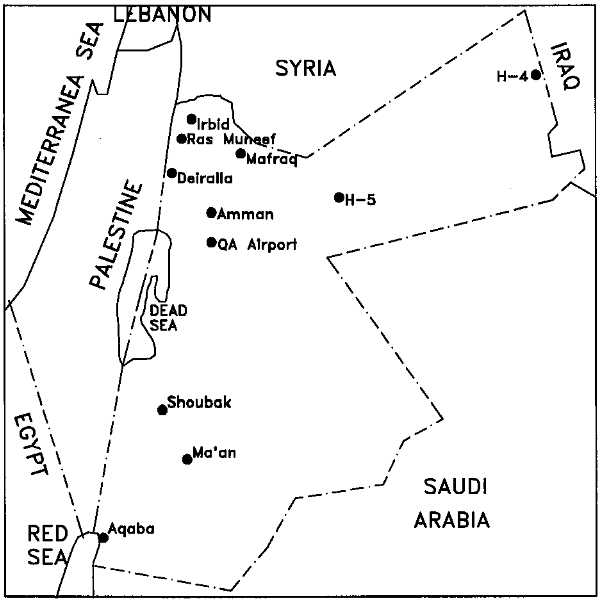

Figure 1. Map of Jordan with wind sites

Quraeshi, 1987a, b; Adell *et al*., 1987; Pandey and Chandra, 1986). In a recent study (Habali *et al*., 1987), an evaluation of wind energy in Jordan, and its application for water pumping and electrical power generation was published. It was found that the monthly average wind speed and wind power density range from 0·7 to 7·2 $m s^{-1}$ and from 2 to 460 $W m^{-2}$, respectively. The annual average wind power density was calculated from the measured speeds of 11 stations distributed all over the country. These stations are shown in Figure 1. They include Amman, Aqaba, Deiralla, H-4, H-5, Irbid, Ma'an, Mafraq, Queen Alia Airport, Ras Muneef, and Shoubak. Their power outputs vary within the range 22–275 $W m^{-2}$

The monthly average wind speeds recorded for the above sites are presented in Figures 2 and 3. In terms of wind speed Ras Muneef, Mafraq, and Aqaba are the three most potential sites among all sites covered. Their annual average power densities are 275, 270, and 202 $W m^{-2}$, respectively (Habali *et al*., 1987).

3. REVERSE OSMOSIS (RO) DESALINATION SYSTEM

The RO system major components include membrane modules, high-pressure pumps, power plant, and energy recovery devices as needed. Brackish or sea water at a high pressure, greater than the osmotic pressure is fed through the membrane. Two major factors controlling the energy requirement of an RO system are membrane properties and salinity of the feed water (Geankopolis, 1983). Higher water salinity requires more energy to overcome the osmotic pressure, where the RO system needs only mechanical power to raise the pressure of feed water. Other advantages of RO systems include low investment costs at low capacities, ease of operation, flexibility in capacity expansion, operation at ambient temperature and short construction periods.

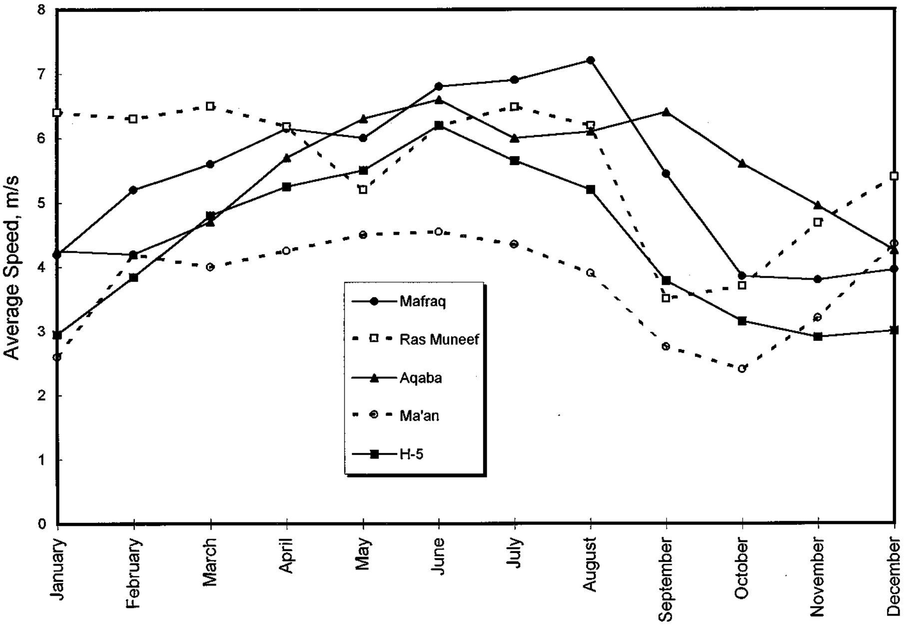

Figure 2. Monthly average wind speeds for Mafraq, Ras Muneef, Aqaba, Ma'an, and H-5 (source: Habali *et al*., 1987)

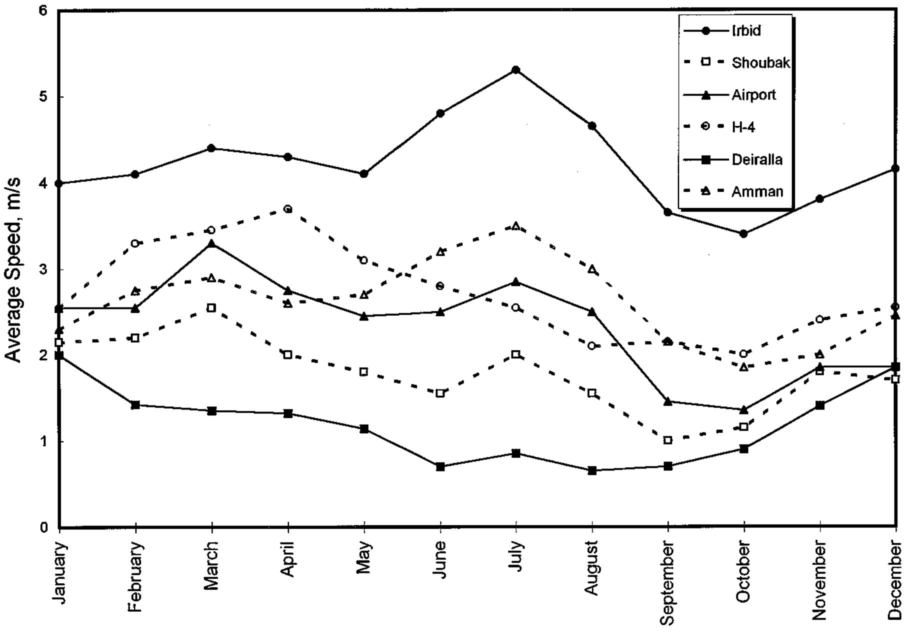

Figure 3. Monthly average wind speeds for Irbid, Shoubak, Queen Alia Airport, H-4, Deiralla, and Amman. (source: Habali *et al*., 1987)

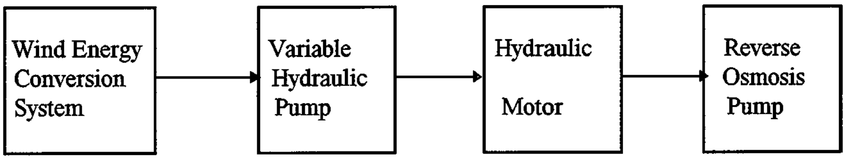

Figure 4. Schematic diagram of RO system driven by wind power

4. WIND ENERGY RO SYSTEM

A RO desalination system driven by wind energy is proposed. The system is mechanically powered, directly coupling the wind energy conversion system (WECS) to a high-pressure pump for use in RO desalination. A schematic diagram of the system is shown in Figure 4. The available power of the WECS is obtained from the following equation:

$$P_{\mathrm{WECS}} = \tfrac{1}{2} C_{\mathrm{p}} \rho A V^3 \tag{1}$$

The energy output from WECS can be represented by

$$E = T \int_0^\infty P_{\mathrm{WECS}} f(V)\,\mathrm{d}V \tag{2}$$

the function $f(V)$ is the probability distribution function of wind velocity, which is generally written as a Wiebull distribution:

$$f(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} \exp\left(-\left(\frac{V}{c}\right)^k\right) \tag{3}$$

where k is a shape factor, and c is a scale factor given by

$$c = \bar{V}\Gamma\left(1 + \frac{1}{k}\right) \tag{4}$$

for a given power output, the energy output equation can be written in the form:

$$E = e_{\mathrm{syst}}(X_{\mathrm{c}}, X_{\mathrm{d}}, X_{\mathrm{r}}, X_{\mathrm{f}}) C_{\mathrm{p}} \tfrac{1}{2} A \bar{V}^3 T \tag{5}$$

Water production over a period of time T is given by

$$W = T \int_0^\infty \frac{P(V)}{\varepsilon(P)} f(V)\,\mathrm{d}V \tag{6}$$

where ε is the energy consumption per unit of product water. If we propose that the wind turbine will deliver effective power to the RO system at wind speeds above V_{r} and shut down at wind speeds exceeding V_{f}. The resulting power can be written in the form

$$P_{\mathrm{w}}(V) = \begin{cases} 0 & 0 \leqslant V < V_{\mathrm{r}} \quad \text{or} \quad V \geqslant V_{\mathrm{f}} \\ P_{\mathrm{wr}} = \tfrac{1}{2} C_{\mathrm{p}} \rho A V_{\mathrm{r}}^3 & V_{\mathrm{r}} \leqslant V < V_{\mathrm{f}} \end{cases} \tag{7}$$

and the water production in the form

$$W = T\left[\left(\frac{1}{2}\right) e_{\mathrm{syst}}(X_{\mathrm{r}}, X_{\mathrm{f}}, k) C_{\mathrm{p}} \left(\frac{1}{\varepsilon}\right) \rho A \bar{V}^3\right] \tag{8}$$

where e_{syst} is written as

$$e_{\text{syst}} = X_{\text{r}}^3 \left[\exp\left\{ -\Gamma^k \left(1+\frac{1}{k}\right) X_{\text{r}}^k \right\} - \exp\left\{ -\Gamma^k \left(1+\frac{1}{k}\right) X_{\text{f}}^k \right\} \right] \tag{9}$$

In order to apply the above-described model, a wind machine and a RO unit were selected. Their characteristics are listed in Appendix A.

5. DISCUSSION

Figures 5 and 6 represent the monthly amount of water produced during a one year cycle, at the different wind sites. Figure 5, for example, represents the most favourable sites for water production. They are Ras Muneef, Mafraq, and Aqaba. The annual amount of water produced in all sites is presented in Figure 7. In terms of water production, the sites can be divided into three different categories; one is considered to be favourable, which includes Ras Muneef, Mafraq, and Aqaba (see also Figure 5). At these three locations alone about 75% of water was produced compared to production from all eleven sites combined. The second category is considered to be promising. It includes Ma'an, H-5, and Irbid (see Figure 6). About 24% of the annual water produced from all sites combined is produced at these three locations. These locations are labelled promising, so that one may consider other alternatives, such as considering other renewable energy method for water desalination and comparison with wind power.

The third category was considered to be poor in terms of water production. That includes the following locations: H-4, Amman, Queen Alia Airport, Shoubak, and Deiralla. As shown in Figure 7, the annual water production at these location was very small; only traces of water can be produced at the given wind speeds. Less than 1% water is produced at these location combined when compared to water production of all eleven

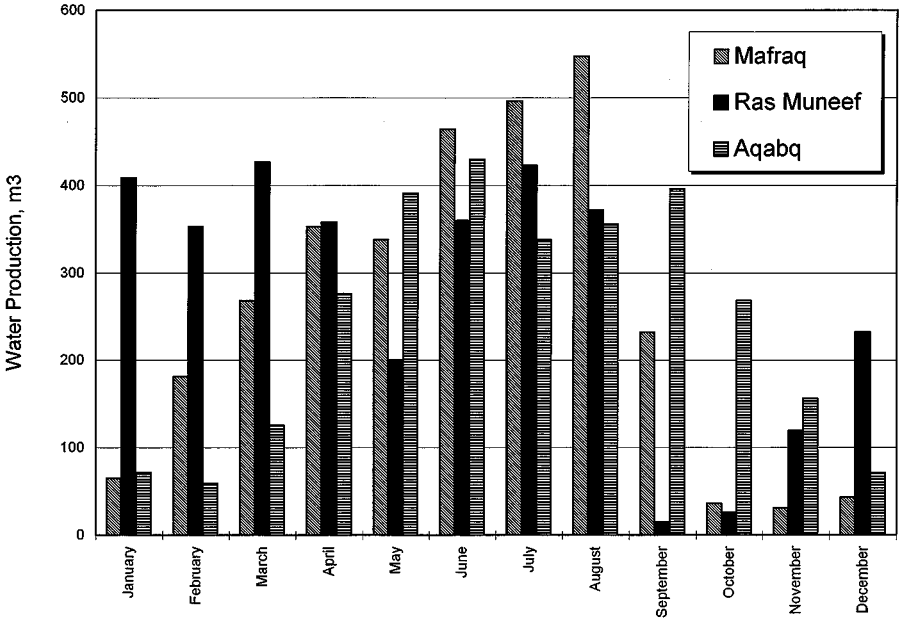

Figure 5. Monthly water produced for Mafraq, Ras Muneef, and Aqaba

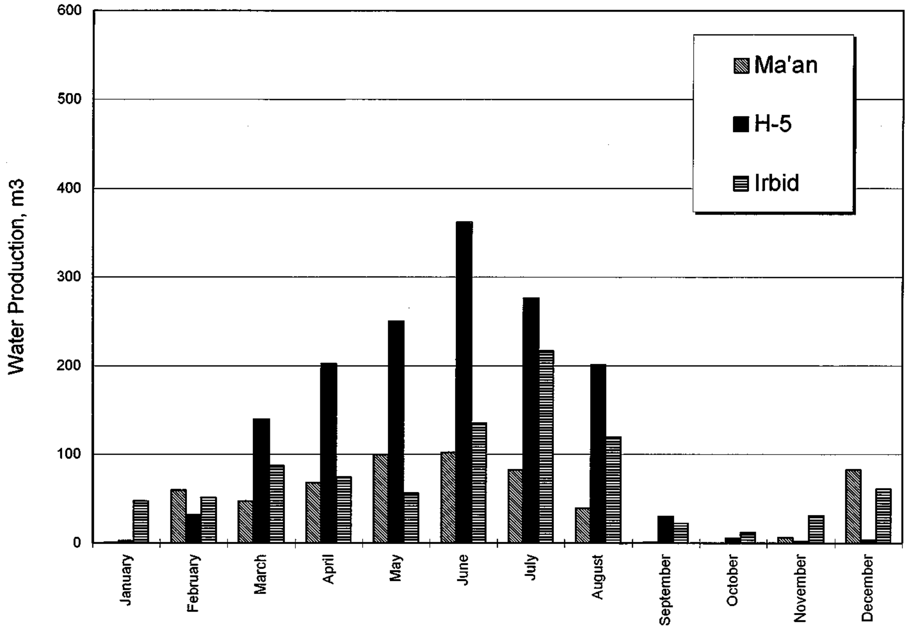

Figure 6. Monthly water produced for Ma'an, H-5, and Irbid

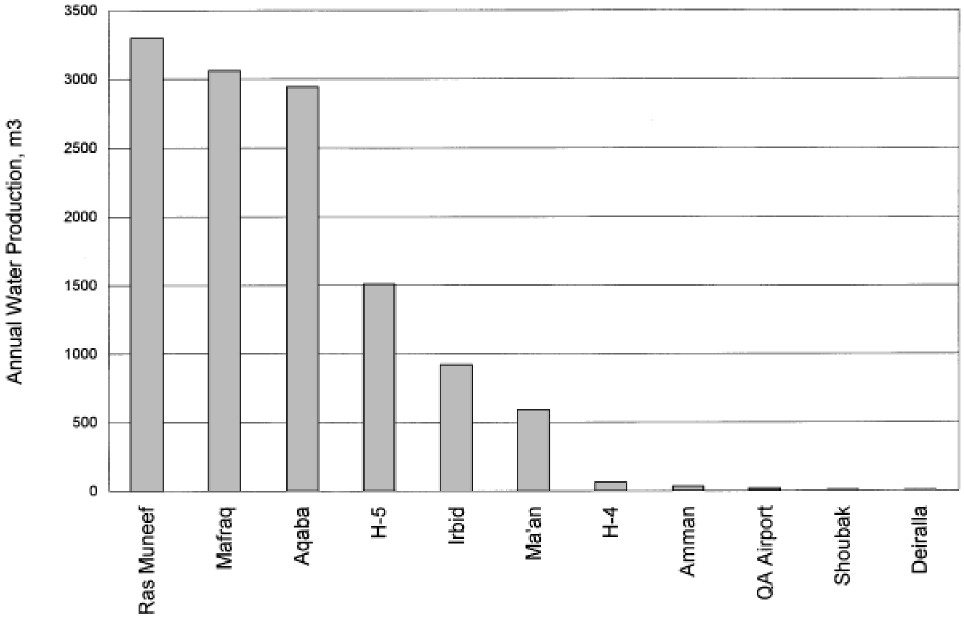

Figure 7. Annual water produced for all wind sites

sites combined. For these locations wind driven RO desalination system may not be the best choice, other methods should very strongly be considered.

Although, Ras Muneef, Mafraq, and Aqaba produced not only the most annual amount of water, but they were very close to each other; what is interesting is that one looks more attractive than the other. On the one hand, 54% of the annual amount of water produced at Ras Muneef takes place during the months December through April. Jordan is characterized as a semi-arid region. These months are considered to be the rainy months by which water is not needed the most. On the other hand, the opposite is true for Mafraq and Aqaba. At Mafraq 57% of annual production of water is during the months of June through September. At this location wind powered RO desalination system would be an excellent choice, when water is needed the most. Similarly, at Aqaba of which about 65% of water is produced during May through September.

6. CONCLUSION

Some wind sites show that they have favourable application towards wind powered water desalination in Jordan (reverse osmosis system). They include Ras Muneef, Mafraq, and Aqaba. However, H-5, Irbid, and Ma'an have shown to be promising. The rest of wind sites, which include H-4, Amman, Queen Alia Airport, Shoubak, and Deiralla are found to be unattractive in terms of wind powered desalination.

NOMENCLATURE

A	swept blade area, m^2
C_p	coefficient of power
c	scale factor
e_{syst}	dimensionless energy output
E	energy output from wind energy conversion system, kWh
k	shape factor
P	power, kW
P_w	power output, kW
P_{WECS}	power of wind energy conversion system, kW
P_{Wr}	power output at rated wind speed, kW
T	time period, days
V	wind speed, $m\,s^{-1}$
$\bar{V}$	average wind speed, $m\,s^{-1}$
V_c	cut in wind speed, $m\,s^{-1}$
V_d	design wind speed, $m\,s^{-1}$
V_f	furling wind speed, $m\,s^{-1}$
V_r	rated wind speed, $m\,s^{-1}$
W	quantity of water produced, m^3
X_c	dimensionless cut in wind speed ($=V_c/\bar{V}$)
X_d	dimensionless design wind speed ($=V_d/\bar{V}$)
X_f	dimensionless furling wind speed ($=V_f/\bar{V}$)
X_r	dimensionless rated wind speed ($=V_r/\bar{V}$)

Greek letters

Γ	gamma function
ε	energy consumption per unit of water produced, $kWh\,m^{-3}$
ρ	air density, $kg\,m^{-3}$

APPENDIX A

Wind Machine and RO Data

Item	Description
Wind machine	• Rated power: 11 kW • Rotor diameter: 11 m • Operating wind speeds: – Cut-in: 3·5 $m\,s^{-1}$ – Rated: 8·5 $m\,s^{-1}$ – Cut-out: 24 $m\,s^{-1}$ – Furling: 50 $m\,s^{-1}$ • ρ: 1·22 $kg\,m^{-3}$
RO desalination unit	• C_p: 0·40 • k: 2·0 • ε: 6·48 $kW\,h\,m^{-3}$

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