

Potential for Wind-Powered Desalination Systems in Jordan

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Abstract

Desalination systems driven by renewable energies are limited, and they usually have a limited capacity. They only represent about 0.02% of total desalination capacity. However, many reasons make the use of renewable energies suitable for brackish and seawater desalination. In addition to shortage of fresh water resources, Jordan is suffering from shortages in recoverable commercial energy sources such as crude oil and natural gas. The limited energy sources in Jordan makes considering renewable energy options such as wind power very attractive, especially for remote areas. This will be extremely important for small-scale applications. Due to prevailing tough conditions, such as low water quality and shortage in supplies, there is a large demand for small desalination units, not only in locations not connected to a water supply network, but also as units for additional or independent supply. The coupling of wind energy and desalination systems holds great promise for increasing water supplies in water scarce regions. An effective integration of these technologies will allow countries to address water shortage problems with a domestic energy source that does not produce air pollution or contribute to the global problem of climate change. Meanwhile the costs of desalination and renewable energy systems are steadily decreasing, while fuel prices are rising and fuel supplies are decreasing. This paper specifically seeks to address the enhancement of the overall quantity of freshwater available in Jordan, by exploring the potential for integrating wind power and desalination technologies to increase water supplies. Both desalination and wind technologies are summarized in this paper, including growth trends, costs, and emerging technological advancements. These descriptions provide snapshots of the current status of these technologies and their markets, as both independent and integrated technologies. Meteorological data is then used to generate a map of Jordan wind-powered desalination potential “hotspots”, to give a rough idea where the integration of these technologies might be the most applicable.

Keywords: *Wind-Powered Desalination, RO Desalination, Renewable Energy, Jordan*

1. Introduction

Water and energy are two inseparable commodities that govern the lives of humanity and promote civilization. The history of mankind proves that water and civilization are two inseparable entities. This is proved by the fact that all great civilizations were developed and flourished near large sources of water. Rivers, seas, oases, and oceans have attracted mankind to their coasts because water is the source of life. History proves the importance of water in the sustainability of life and the development of civilization.

Desalination of sea and brackish water seems to offer a sound alternative to arid lands bordering seas or salt lakes; desalination plants producing up to several million gallons per day are commercially available and already used for domestic and industrial purposes in some very arid regions. The major limitation of desalination is its high energy requirements, and

therefore it is useful to explore how renewable energy resources can be linked into desalination systems for sustainable freshwater production into the future, considering the technological advancements and costs. Also, conventional energy supply is not always possible in remote areas: on the one hand because of difficulties in fossil fuel supply, and on the other because the grid does not exist or the available power is not enough to drive a desalination plant. In such cases, the use of renewable energies permits sustainable socioeconomic development by using local resources.

Jordan lies in the heart of the Middle East and is amongst the low-income countries of the region, with an average GDP per capita of about US\$2000 in 2004 [1] as compared to about US\$10,000–18,000 for neighboring Arab countries, with the exceptions of Syria, Yemen, Palestinian National Authority and Egypt [2]. On the other hand, Jordan is a nonoil-producing country. It relies, almost completely, on imported oil from neighboring countries, which causes a financial burden on the national economy. In 2004, even with a relatively moderate

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DOI: 10.5383/ijtee.01.02.007

unit price for crude oil in the international market, about US\$1.65_109 was spent on imported crude oil, refined petroleum products and natural gas [3]. This value represents approximately 15% of the GDP, 20% of the total imports and more than 41% of the domestic commodities exports. However, Jordan has abundant supplies of new and renewable energy sources, such as oil shale and solar energy. Nevertheless, crude oil has primarily dominated the Jordanian energy sector for the last four decades and still does; it has been the chief energy source for economic and social developments. Such a tough situation should make energy scarcity the main driving force behind energy saving schemes in various sectors.

2. Jordan's Water Recourses Overview

The potential for water resources in Jordan ranges from 1,000 to 1,200 MCM, including recycled treated wastewater. Water resources consist primarily of surface and groundwater, with treated wastewater being used on an increasing scale for irrigation, mostly in the Jordan Valley. Renewable water resources are estimated at about 750 MCM per year, including groundwater at 277 MCM/year and surface water at 692 MCM/year, of which only 70% is economically usable. An additional 143 MCM/year is estimated to be available from fossil aquifers. Brackish aquifers are not yet fully explored, but at least 50 MCM/year is expected to be accessible for urban use after desalination [4].

Domestic supply of water to Jordanian population depends mainly on groundwater aquifers. Those aquifers, however, are under severe pressure from the agricultural sector, which consumes about 70% of resources, and the rest is used for municipal and industrial consumption. It is noteworthy that the contribution of agriculture to the Jordanian GDP is only 6% [5].

Groundwater is considered to be the major source of water in Jordan, and the only source of water in some areas of the country. Twelve groundwater basins have been identified in Jordan. Most basins are comprised of several groundwater aquifer systems. The long term safe yield of renewable groundwater resources has been estimated at 275 MCM/year. Some of the renewable groundwater resources are presently exploited to their maximum capacity, and in some cases beyond safe yield. Overexploitation of groundwater aquifers, beyond the annual potential replenishable quantities, has and will contribute significantly to the degradation of groundwater quality in the exploited aquifers, and endangers the sustainability of these resources for future use.

The main nonrenewable groundwater resource in Jordan exists in the Disi aquifer in the South, with a safe yield of 125 MCM/Year for 50 years. Other nonrenewable groundwater resources are estimated at an annual safe yield of 18 MCM [4]. The three major surface water systems in Jordan are the Jordan, Zarqa and Yarmouk, but all have become highly undependable. For the Jordan and Yarmouk Rivers, this is due to upstream diversion and over-pumping by Syria and Israel, leaving Jordan with the rest. The Zarqa River system has been severely affected with water pollution from industries in the Amman-Zarqa area, which includes 70% of Jordanian small-medium sized industries.

The King Talal Dam is Jordan's largest aboveground reservoir, but it faces two problems. Erratic surface water levels often reduce trapped levels to below the total capacity of 86 MCM.

Also, pollution from factories that dump untreated waste into tributaries leading to the dam is raising salinity, chemical, and metal levels.

Treated wastewater, generated at sixteen existing wastewater treatment plants, is an important component of Jordan's water resources. Due to the topography and the concentration of urban population above the Jordan Valley escarpment, the majority of treated wastewater is discharged into various watercourses, and flows downstream to the Jordan Valley, where it is used for irrigation. Currently around 55 MCM of treated wastewater is used for restricted irrigation purposes in the country. The Ministry of Water and Irrigation MWI forecasts state that the amount of wastewater used for irrigation should reach 232 MCM by 2020, especially in the Jordan Valley [6].

The existing wastewater treatment plants are over-used beyond their design capacity due to increased inflow of wastewater. This has reduced the quality of treated wastewater, and this "resource" has not been effectively used to gradually replace freshwater resources in agricultural uses.

2.1. Analysis of Demand and Supply of Water

Sustainable water supply in Jordan is limited, whereas demand is rising rapidly. The demand in the year 2002 was around 1,000 MCM, of which 450 MCM was derived from surface water while the rest came from renewable and non-renewable groundwater. To meet the deficit between supply and demand, the groundwater aquifers are mined at a rate of 200 MCM annually. This corresponds to about 160% of the aquifers' sustainable yield [7].

A model of water demand developed by the MWI and the World Bank in 2001 indicated that water requirements will continue to increase as a result of increasing population, including the cumulative impact of past refugees, rising living standards, industrial development and an increase in scale and intensity of cropping activities in the Jordan Valley [4].

The present annual water demand amounts to 10% of the annual total rainfall on the country. Almost all the economically viable surface water resources in Jordan have been harnessed, mainly for irrigation purposes. The few remaining sources will be relatively expensive to develop. The groundwater resources of the country are over-exploited; some basins have been completely depleted and the rest, if present trends persist, will run dry within a few years. The depletion of groundwater resources is increasing the salinity of the remaining available water, and so action must be urgently taken to prevent this over-pumping.

Currently, it is estimated that sustainable annual water supply per capita in Jordan is less than 200 CM. Increasing water demand for domestic and industrial purposes is expected as a result of the high population growth rate, and improvements in living standards and the anticipated developments in the tourism and industrial sectors. The amounts of water used for irrigation may have to be reduced in order to satisfy such needs. Increased effectiveness in irrigation, and reallocation from irrigation to other uses, could provide sufficient renewable water to meet the growing domestic demand, at least for the next decade.

The predictable water deficits are high and increasing. Because some potential renewable resources are so expensive to harness, the volume of economically available water is far

lower than what could be harnessed annually. Jordan is likely to suffer severe water-rationing early this decade.

The main reason for this high use of water in agriculture is related to the low quantity of surface water available for agriculture, and the fact that the small percentage of land which receives more than 300 mm of rainfall is almost entirely covered by urban development, leaving only dry land to be cultivated. This is exacerbated by the low soil quality and high evaporation rates.

The industrial sector uses around 60 MCM annually and is still growing. The main industrial base in Jordan is the mining and extractive industry, especially for phosphates, cement and potash. All these industries are highly water demanding. Other small-medium scale industries have been suffering from shortages in water supply and increase in their costs. They have opted for more water-conservation efforts in industrial processes by recycling their wastewater streams wherever feasible. The water shortage has also been a limiting factor in the establishment of new industries, as well as expansion of some high-potential energy industries like oil shale.

3. Energy Resources in Jordan

Jordan is a nonoil-producing country. It relies, almost completely, on imported oil from neighboring countries, which causes a financial burden on the national economy. In 2004, even with a relatively moderate unit price for crude oil in the international market, about US\$1.65x10⁹ was spent on imported crude oil, refined petroleum products and natural gas [3]. This value represents approximately 15% of the GDP, 20% of the total imports and more than 41% of the domestic commodities exports. However, Jordan has abundant supplies of new and renewable energy sources, such as oil shale and solar energy. Nevertheless, crude oil has primarily dominated the Jordanian energy sector for the last four decades and still does; it has been the chief energy source for economic and social developments. Such a tough situation should make energy scarcity the main driving force behind energy saving schemes in various sectors. In 2004, the total primary and final energy consumption were about 6.5x10⁶ and 4.6x10⁶ toe, respectively. The latter was distributed between transport (38%), residential (22%), industrial (23%), services and commercial (9%), and other minor sectors (8%) (see Fig. 1). The rate of energy consumption, especially electricity, is rising rapidly due to the high growth rate of population and urbanization. Residential energy requirements may vary from one province to another, depending on the standard of living, type and age of dwelling, climate conditions and availability of different forms of commercial energy sources. One of the key findings of a recent field survey conducted by the Ministry of Energy and Mineral Resources, in order to determine the energy consumption trends in the household sector in Jordan, is that space heating represents about 61% of the total energy consumed in the residential sector [8]. Thus any action to improve energy efficiency in this sector should take into account the need for analyzing and studying different ways of space heating and opportunities to reduce the envelop energy losses, while simultaneously maintaining inside of the house comfortable. Many researchers addressed some prospects of energy savings in the residential and commercial sectors, and the main conclusions were to improve thermal insulation of buildings, increase dependence on renewable energy sources and to conduct comprehensive public awareness campaigns, aiming to enhance the utilization of proven more effective, higher efficiency applications and techniques [9–11].

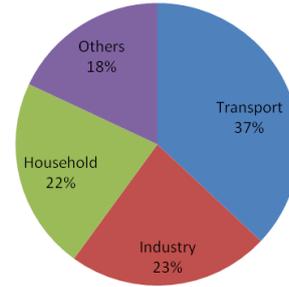


Fig. 1. Distribution of final energy consumption

4. Renewable Energy Resources in Jordan

Renewable energy is considered the largest domestic energy source together with oil shale. Technical and market potential exists to increase significantly the contribution of renewable energy sources to Jordan's energy balance, resulting in employment and economic benefits. However, the contribution of such resources in the national energy mix is still minor. For the long-term future, ensuring the security of energy supplies is a highly important issue, but this is regarded as of minor importance relative to the more immediate social and economic problems facing Jordan. Efforts have been made to promote the use of renewable energy, such as wind, solar and biomass, but these are not likely to make more than marginal contributions to the national energy balance during the next 15 years, unless attitudes change and energy unit prices rise significantly. This is because harnessing renewable energy has in general been more expensive per unit of energy than that obtained from conventional energy sources. But it is environmentally beneficial. Nevertheless, renewable energy provides approximately 1.5% of the total current primary energy demand in Jordan [12]. In the following sections each domestic renewable energy sources is presented briefly.

4.1 Solar energy

Jordan has abundant supplies of solar energy, with relatively high average daily solar radiation of 5.5 kWh m⁻² day, since it lies in the "global sunbelt" between 29°11' and 33°22' N latitudes. The annual sunshine duration is around 2900 hours, which can be considered sufficient to provide enough energy for solar heating/cooling applications. Nevertheless, solar energy technologies are not extensively used, except for solar-water-heaters (SWH), which used for heating of domestic-water. The SWH industry, in Jordan, is well developed. The main solar system produced locally is the thermosyphon-type. The typical SWH system, for average family, consists of three flat-plate solar collectors having a total absorbing area of between 3-4 m², a cold and hot water storage tanks with capacity of about 1000 and 150 liters, respectively. All of these are installed together on a steel frame, the collectors are tilted and face south, and hot tank is thermally insulated to keep water inside warm during off-sunny hours. However, solar energy is not harnessed via solar water-heating systems for space heating, and its use is limited to the supply of domestic hot water for about a quarter of the housing stock, i.e. 2.2x10⁵ homes, in Jordan [13-14]. Thereby avoiding the need for approximately 1.5% of the total oil imports, with an associated savings of about 13 million US\$ annually.

4.2 Wind energy

Wind turbines are the natural evolution of traditional windmills, which were used by ancient civilizations thousands of years ago. Wind power technology harnesses one of the most abundant natural resources in the generation of electricity without harmful waste products or emissions. During the last few years, there has been a great interest to exploit wind energy in different countries, especially in Europe, to counter the increasing rates of greenhouse gas emissions. Throughout the 1990s, world wind power generation has grown at a high rate of about 22.2% per annum, while solar energy has grown at 15.9% annually. On the other hand, demand for crude oil, which is the world's dominant energy source, has grown at just 1.8% per year. By the end of the last century, perhaps as a direct response to the Kyoto Protocol, many governments and large international companies have announced major new investments in giant wind farms, solar manufacturing plants and fuel-cell development. Such developments of wind power around the world have been driven by governments as a result of placing a high value on the economic and environmental benefits of wind power. There are a number of regions in Jordan with acceptable wind speed to generate electricity, where the great potential areas are the northern and southern parts. The country is classified into three wind regions according to prevailing wind speed: less than 4 m/s, between 4 and 6 m/s and more than 6 m/s for low, medium and high regions, respectively. But the high wind regime is limited to certain districts: most attractive sites are Hofa, in the northwestern corner and Fjeij, near Showbak, and Wadi Araba in the south. Jordan's first wind farm, with a gross capacity of 320 kW in Ibrahimyya close to Hofa, was commissioned in 1988. This pilot project was successful technically and financially: average annual generated electricity is about 650 MWh. The experience gained from this project and the mutual co-operation with the German Government, under the special technical assistance program named Al-Dorado, resulted in a new wind-electric power installation of 1.125 kW nominal capacity, in Hofa. The project was connected to the national grid in 1996 and became fully operational in 1997. At present, the annual rate of power generation from wind turbines, in Jordan, is 2.9 GWh, thereby avoiding the need for approximately 800 toe, i.e. 0.044% of the total annual energy consumption in the power sub-sector. The corresponding savings in fuel cost is about US\$0.15 million annually, at current prevailing prices. More important is the sustainable and diversified electricity supplies. On the other hand, wind energy is being utilized to empower several small demonstration projects for water pumping in isolated areas: monitoring and evaluation of these projects is continuing. There is a growing interest in utilizing wind energy and other renewable sources in Jordan. The government has removed the legal obstacles by modernizing the General Electricity Law. The environment for non-conventional power sources was changed completely, and for the first time enabled independent generators to be established in the country. Although it is not specifically mentioned in the modified Electricity Law, the rules governing the operation of renewable power projects are those applicable to conventional generators. The most important of these are: the installed capacity of the renewable electricity plant should be over 5 MW; electricity should be generated at competitive prices; and the National Regulatory Commission will set the tariff. In addition, such projects will qualify for incentives granted under the "Investment Promotion Law". The latter includes exemptions of fixed assets and spare parts from customs duties and taxes; protection against expropriation; and special depreciation schedules. More importantly, under the

United Nations Framework Convention on Climate Change (UNFCCC) guidelines, all renewable-based future electricity generation projects will be valid and open to investors under the Clean Development Mechanism (CDM). Thus, Jordan could participate in projects as part of the CDM, which is designed to assist both developed and developing countries in achieving sustainable development and compliance with their emission limitation and reduction commitments, respectively. Recently, the government, represented by the Ministry of Energy and Mineral Resources, invited interested native and foreign investors to submit their financial and technical proposals to develop wind parks at the three pre-selected locations in the most promising sites, on a build-own-operate (BOO) basis. In each location, windmills will have a total installed capacity of about 25–30 MW along with supporting facilities. The generated power will be supplied directly to the national electrical grid. By 2005, it is predicted that green electricity, from these wind farms, will be available to consumers in Jordan [15-23].

4.3 Geothermal energy

Jordan is among countries with moderate potential in geothermal energy. However, all surveyed hydro-thermal fields are of low temperature, i.e. less than 100 °C, and located in two main regions: namely the eastern flank of the Jordan Valley, in the west, and the plateau east of Madaba city. Hence, the commercial utilization of these fields will be limited and they will not be used for electrical power generation. Nevertheless many of these sources are currently used on a small scale either for hot-water spas or for greenhouse heating. In the future, the government of Jordan should look at utilizing such energy sources for space and water heating, i.e. geothermal central heating [24-25]. This is less costly than burning fossil fuels in conventional heating systems and could be feasible for many regions in the country. Heat pumps have the advantage of converting low grade heat into useful heat. Heat pumps can extract waste heat from ventilation air or process wasteful streams and make it suitable for reuse. Even in winter, the outside air, water and ground still retain heat, which can be extracted and upgraded by a heat pump. This natural heat can be used for various applications, such as space and water heating and even in industrial processes as well as commercial buildings.

4.4 Municipal solid waste and biomass

Biomass energy includes all fuels derived from biological sources, such as charcoal, agricultural, animal and municipal wastes. It is reported that almost 50% of the world's population, especially in developing countries, use these sources for cooking and/or heating, and they account for about 14% of the total world energy consumption [26-29]. Energy from biomass in Jordan has, as yet, achieved little significance and only appears to offer a low potential because of the severe constraints on vegetation growth imposed by the arid climate. Direct combustion of biomass provides some energy for cooking and heating in rural areas: it is the main source of energy for Bedouins in the desert. It has been estimated that animal and solid wastes in Jordan represent an energy potential of about 105 toe annually, but municipal solid waste represents a major fraction with a gross annual production rate of approximately 1.1 million tonnes. The daily average per capita varies between 0.35 kg and 0.95 kg in rural and urban regions, respectively, of municipal solid waste, and the typical gross calorific value is between 7 and 11 MJ/kg, following seasonal variations. The utilization of bio-energy in the form of

biogas from animal and domestic wastes has also been investigated, with the aim of introducing a family fermentation unit, which produces biogas for domestic purposes.

4.5 Hydropower

Hydropower sources are limited due to the fact that the surface water resources, such as rivers and falls, are almost negligible. However, currently there are two small hydropower schemes. The first is the King Talal dam spanning the river Zarqa, with a rated electricity generating capacity of 5 MW. The other scheme is at the Aqaba thermal power station, where the hydro-turbine utilizes the available head of returning cooling seawater with a capacity of 5 MW. The total amount of electricity generated, in 2001, by hydro- units was 42.7 GWh, i.e. 0.56% of the total national electricity generation. This represents, at present, the total economically feasible capacity for hydropower in Jordan. However, there is a great possibility to generate electricity, using hydropower stations, by exploiting the elevation difference between the Red and Dead Seas. The latter is the lowest region on earth with its water surface 400 m below normal sea level. If seawater is allowed to flow from the Gulf of Aqaba into the Dead Sea through a canal system at predetermined rates, it will produce electrical power from hydropower stations and potable water from seawater desalination plants. While this project is expected to help in establishing new economic activities, such as tourism and agriculture, it will ensure the supply of large amounts of highly needed electricity and water as well as the replenishment of the Dead Sea by replacing the evaporated water. The latter will dictate the amount of electricity generated annually. Preliminary pre-feasibility reports have shown that it is possible to build hydropower stations with a total capacity of 400–800 MW. But the required capital investment is extremely high due to the long canal, i.e. about 200 km, and necessary infrastructure [30].

5. Desalination

The process of generating fresh water from seawater, or desalination, has been in operation for over 50 years [31]. The impetus for the development of this technology is clear as saltwater makes up 97.5% of water resources on the planet, representing an effectively limitless source of freshwater in the context of desalination [32]. In addition, 40% of the world’s population lives within 60 km (37.3 miles) of the coast suggesting that the benefits of desalination have the potential to reach a large target population. However, it is important to

state that desalination should not be viewed as the panacea for the world’s water problems. The utility of desalination is generally recognized as being limited by its costs, energy requirements and geography. Therefore, desalination processes should be viewed as a supplement to existing water supplies, and should only be implemented in conjunction with pollution prevention and demand management programs to protect and improve the efficiency of use of current water supplies.

Many desalination technologies currently exist and are in operation at various scales around the globe, allowing human populations and industries to grow and thrive in previously inhospitable locations. Two basic technologies are utilized to remove the salts from ocean water: thermal distillation and membrane separation. See Figure 2 below for a categorization of desalination technologies. This section addresses only those technologies identified by the large red boxes, as these are the most widely adopted desalination technologies. Eventually, the potential of using indirect solar through a wind energy converter will be discussed.

5.1 Thermal distillation

Thermal distillation technologies in their various forms all depend on the same concept: converting saltwater to steam and then condensing and collecting the freshwater distillate. Thermal distillation units began to be installed in the 1960s at a commercial scale, or up to 8,000 cubic meters per day [33]. The three basic technologies for thermal distillation include: Multi-Stage Flash (MSF) Distillation, Multi-Effect Distillation and Vapor Compression. All three of these distillation technologies are based on converting salt water to steam in a series of chambers of progressively reduced pressure. The reduced pressure allows the saltwater to boil at lower temperatures, thereby requiring less thermal energy input. MSF and MED processes tend to be on a larger scale than VC, although VC units are sometimes used in combination with the other processes. For schematic drawings of these three types of thermal distillation.

5.2 Membrane technologies

Membrane technologies rely on the basic process of using selective membranes to separate salts from water molecules. Membrane technologies began to be commercially viable in the 1970s, and include two basic processes: Reverse Osmosis (RO) and Electrodialysis (ED). Figure 3 below illustrates the basics of Reverse Osmosis plant.

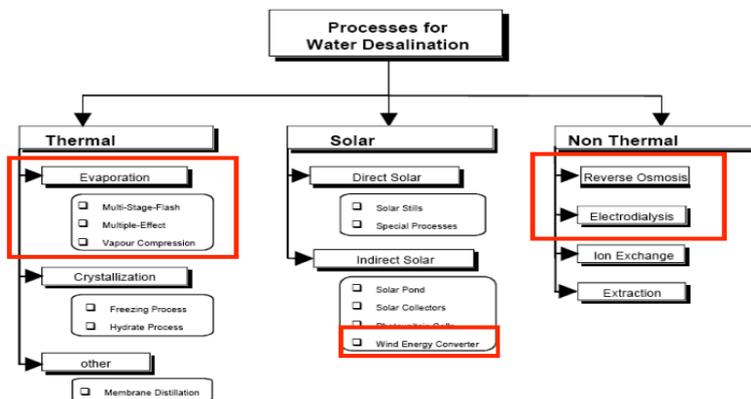


Fig. 2. Categories of Desalination Processes

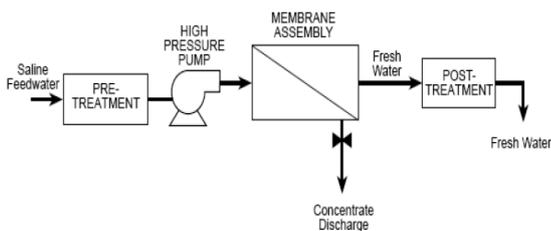


Fig. 3. Basic Reverse Osmosis (RO) Plant

Both processes require energy inputs to overcome the existing osmotic pressure between fresh water and saltwater. ED technology is usually limited to brackish feed water, while RO technologies can be used with brackish waters (BWRO) or seawater (SWRO). Electrodialysis (ED) was developed about 10 years before RO and uses electric currents to draw salts

through a selective membrane, leaving behind a freshwater effluent. Reverse Osmosis (RO) relies on forcing salt water against membranes (usually made of cellulose acetate or aromatic polyamide) at high pressure, so that water molecules can pass through membranes and the salts are left behind as a briny concentrate [34].

5.3 Comparison of Technologies

The selection of an appropriate desalination technology depends on a range of variables, including: type of feed water, energy source, quality of freshwater output and plant size. Table 1 below compares the major technologies based on these variables.

Table 1. Characteristics of the Major Desalination Processes [35]

Process	Feed Water Type	Energy Source	Product Water Quality (ppm TDS)	Typical Max Plant Capacities (m ³ /day)	Typical Energy Requirements (kWhe/m ³)
Multi-Stage Flash Distillation (MSF)	Seawater	Steam	~10	5,000-60,000	10-14.5
Multi-Effect Distillation (MED)	Seawater	Steam	~10	5,000-20,000	6-9
Vapor Compression (VC)	Seawater	Electricity	~10	2,400	7-15
Seawater Reverse Osmosis (SWRO)	Seawater	Electricity	~350-500	128,000	4-6* 7-13*
Brackish Water Reverse Osmosis (BWRO)	Brackish	Electricity	~350-500	98,000	0.5-2.5
Electro dialysis (ED)	Brackish	Electricity	~350-500	45,000	0.7-2.5

As shown in Table 1 above, all processes work well with seawater except ED, which is limited to treating brackish waters. RO is capable of treating either seawater or brackish waters. Using RO, brackish waters require significantly less energy to process and allow for a higher recovery rate than seawater (25-40% recovery for SWRO and 65- 85% recovery for BWRO), [34], so operational costs for SWRO systems tend to be 3 to 5 times greater than BWRO systems [35].

Energy sources vary across the technologies, with MSF and MED technologies relying upon thermal energy and VC, RO and ED processes requiring electricity. The use of steam for thermal distillation processes allow for the efficient integration of these technologies with power plants or other industrial processes that produce waste heat. Alternatively, the electrical input for VC, RO and ED technologies make these processes more suitable for integration with electrical generators, including renewable sources such as wind turbines and solar photovoltaics. The different processes do not produce the same quality of water. Distillation processes produce higher quality freshwater, with total dissolved solids averaging about 10 parts per million of total dissolved solids (ppm TDS) in comparison to membrane processes which produce freshwater with approximately 350-500 ppm TDS (see Table 1 above). The WHO standards for potable water allow for a maximum value of 1500 ppm TDS [35]. So even though the freshwater produced by membrane processes is of lower quality than distilled water, it is still well below WHO maximum standard for TDS. Some RO plants include a secondary treatment process to further improve water quality and remove the taste of salt residue, but this process is not required for health reasons.

Finally, Table 1 shows the typical maximum production capacities for each desalination technology. SWRO plants demonstrate the greatest maximum capacity with 128,000 cubic meters per day (m³/d) followed by BWRO (98,000 m³/d), MSF (60,000 m³/d), ED (45,000 m³/d), MED (20,000 m³/d), and lowest capacity represented by VC (2,400 m³/d). It is important to note that these numbers represent *typical* maximum capacities, and do not represent actual production limits of each technology. Additionally, while RO is capable of high capacity production, it is also well suited for small and even micro-installations. The RO systems are modular, so membranes and pumps can be successively added to increase the capacity of RO installations.

Figure 4 below shows results from a 1998 inventory of desalination plants, illustrating that MSF technology is the most widely adopted process around the world at (44% of desalination technology) with RO technology close behind (42%).

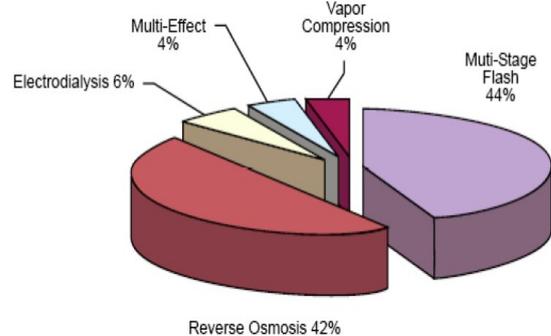


Fig. 4. Distribution of Global Desalination Operations by Technology [33]

This distribution suggests that of the currently available technologies, MSF and RO have historically been the most preferred technologies for desalination. As the current technologies continue to be refined and new technologies are developed, it is likely that this distribution will change in relation to the relative costs of the technologies.

The installation of desalination technology has grown steadily around the world.

Figure 5 below shows that capacity has increased from essentially 0 to over 22.5 million cubic meters per day (~6,500 million gallons per day) between 1965 and 1998.

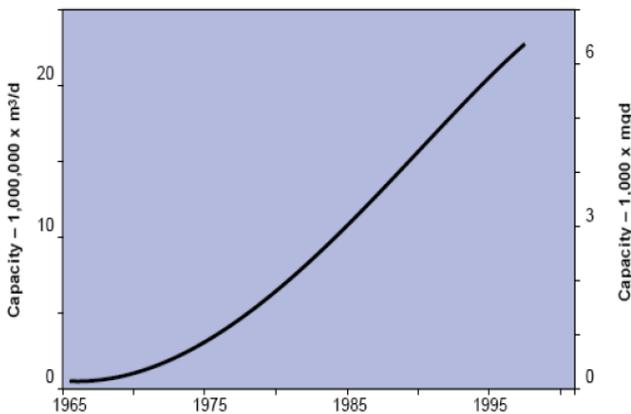


Fig. 5. Total Installed Capacity of Desalting Facilities [33]

As global demand for freshwater increases and global supplies decrease (as a result of pollution, saltwater intrusion and groundwater overexploitation), it seems that this growth trend in the desalination market will continue well into the future. Additionally, advances in desalination technology and increasingly competitive production costs will likely add to the potential for future growth.

Among the various technologies for desalination, Reverse Osmosis (RO) seems to be growing at the fastest rate (approximately 12% annual increase or 200% overall increase between 1988 and 1997) as evidenced by Figure 6 below. The rapid growth potentially signifies technological advancements and reduced energy requirements that have lowered the cost of RO relative to the other methods for desalination.

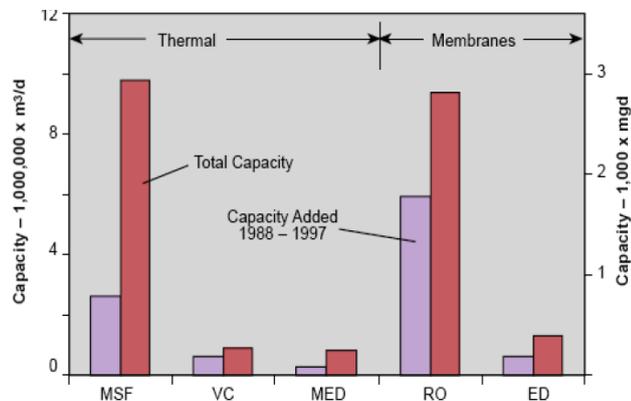


Fig. 6. Distribution of Desalination Capacity by Type of Technology [33]

Membrane-based desalination plants generally require less time for construction than thermal plants. Large MSF installations can take between three to five years, while large RO plants can be constructed in 18 to 24 months. Meanwhile, small-scale RO operations can be installed in four to five weeks [35].

The International Desalination Agency publishes an inventory of all existing desalination plants with pertinent information relating to location, type of process used, feed water characteristics, cost of production, quality of water produced, type of energy input and other pertinent variables. However, due to financial constraints, this author could not afford to purchase the data set, so the distribution information below is an incomplete set of installations around the world. Table 2 below shows desalination installations in seven countries. Of these countries, Saudi Arabia has 48.8% of the total installed capacity and the US has the second greatest capacity at 26.8%. It is also important to note that 48.5% of the capacity in these countries is covered by MSF technology, followed by RO technology at 39.8%.

Table 2. Installed Desalination Plants Capacity (in thousands of m3/d) [35]

Country	MSF	MED	VC	RO	ED	Total	%
Saudi Arabia	2700		50	1000	94	3844	48.8
USA	50	50	130	1600	280	2110	26.8
Kuwait	350			50		400	5.1
Libya	400			130	67	597	7.6
Spain	56		40	230	45	371	4.7
Italy	200		75	40	50	365	4.6
Algeria	60		30	80	16	186	2.4
Total	3816	50	325	3130	552	7873	100
Percent (%)	48.5	0.6	4.1	39.8	7.0	100	

6. Desalination and Renewable Energy

The coupling of wind energy and desalination systems holds great promise for increasing water supplies in water scarce regions. An effective integration of these technologies will allow countries to address water shortage problems with a domestic energy source that does not produce air pollution or contribute to the global problem of climate change. Meanwhile the costs of desalination and renewable energy systems are steadily decreasing, while fuel prices are rising and fuel supplies are decreasing [36].

Finally, the desalination units powered by renewable energy systems are uniquely suited to provide water and electricity in remote areas where water and electricity infrastructure is currently lacking.

The study of the potential interface between desalination and renewable energy technologies has increased significantly in the last five years. Considering that the energy requirements for desalination continues to be a highly influential factor in system costs, the integration of renewable energy systems with desalination seems to be a natural and strategic coupling of technologies.

Renewable energies can power desalination plants through three types of energy media: thermal (heat), physical (shaft) and electrical. Figure 7 below shows the types of desalination technologies most appropriate for the various sources of renewable energy.

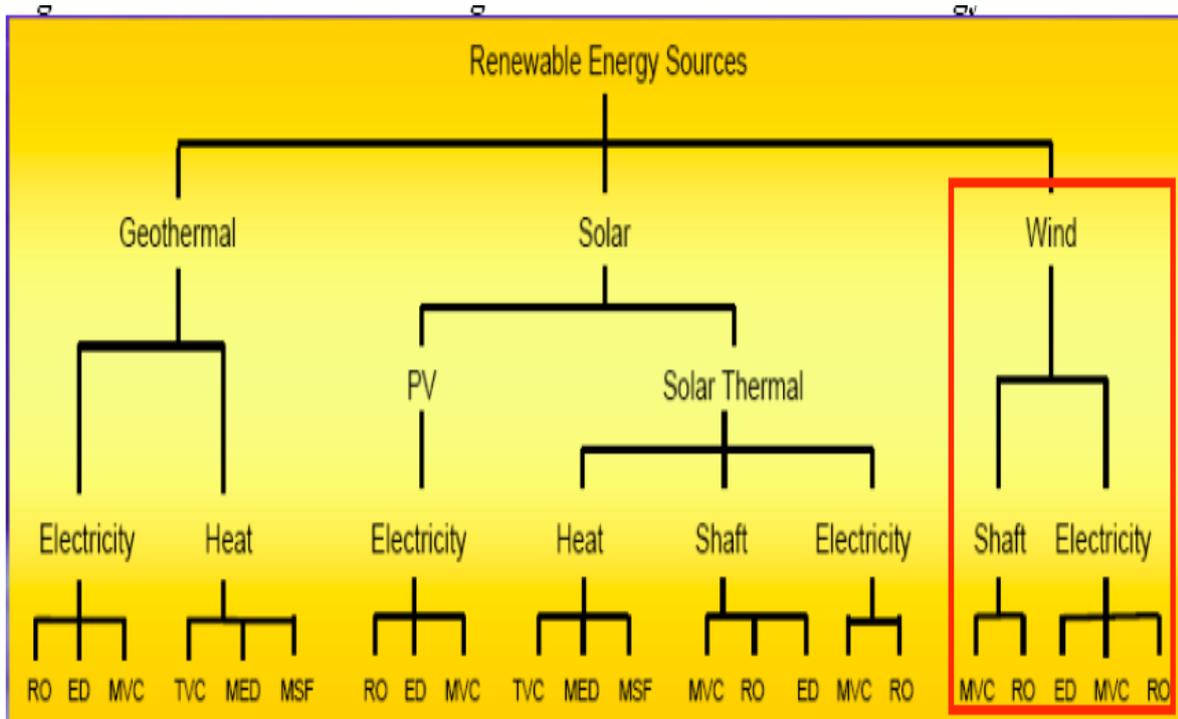
The red box outlines the integration of wind power and desalination systems, which is the focus of this paper. Considering the costs and effectiveness of both desalination and wind energy technologies are highly site specific, when these technologies are integrated the site location becomes even more critical for a successful installation. The quote below summarizes the variables that influence a renewable energy-based desalination plant:

- The viability of any RES [Renewable Energy Systems] desalination combination will mainly depend on:
- The renewable energy potential at the particular site and the form of useful energy which is available after conversion from renewable sources, be it thermal, mechanical, electrical.
- The required production capacity from the desalination plant; this capacity somehow determines the size of the energy collection subsystem.
- The availability of maintenance and experienced personnel for plant operation at the particular site.
- The total system cost.

Fig. 7 below shows the relationship between various energy inputs and criteria for desalination technologies. This analysis suggests that while wind is well suited for desalination process requiring electrical power, wind energy can be problematic as an energy source because it is highly location dependent and has intermittent power output.

However, Table 3 seems to overestimate the problem of wind predictability. While wind is intermittent, it is somewhat predictable as long as there is sufficient historical wind data. Given thirty years of wind speed data, it is reasonable to assume an average annual wind velocity, and therefore calculate potential annual energy output.

As a result of these many influential criteria for determining the best combination of renewable energy (RES) and desalination technologies, there is a broad range of existing installations of RES desalination facilities. As evidenced by Figure 8 below, wind-powered RO systems make up approximately 19% of total RES desalination facilities, second only to photovoltaic-powered RO units (32%).



PV = Photovoltaic Solar, RO = Reverse Osmosis, ED = Electrolysis, MVC = Mechanical Vapor Compression, MED = Multi-Effect Distillation, Multi-Stage Flash Distillation, TVC = Thermal Vapor Compression

Fig.7. Desalination Technologies Available for Renewable Energy Sources [36]

Table 3. Evaluation of renewable energy technologies [34]

Criterion	PV	Solar thermal energy	Wind energy	Geothermal energy
Suitability for powering desalination plants	Well suited for desalination plants requiring electrical power (3)	Well suited for desalination plants requiring thermal power (3)	Well suited for desalination plants requiring electrical power (3)	Well suited for desalination plants requiring thermal power (3)
Site requirements and resource availability	Typically good match with need for desalination (3)	Typically good match with need for desalination (3)	Resource is location-dependent (2)	Resource is limited to certain locations (1)
Continuity of power output	Output is intermittent (energy storage required) (1)	Output is intermittent (energy storage required) (1)	Output is intermittent (energy storage required) (1)	Continuous power output (3)
Predictability of power output	Output is relatively unpredictable (2)	Output is relatively unpredictable (2)	Output is very unpredictable / fluctuates (1)	Output is predictable (3)

Note: 3 = excellent compliance with criterion; 2 = good compliance with criterion; 1 = poor compliance with criterion.

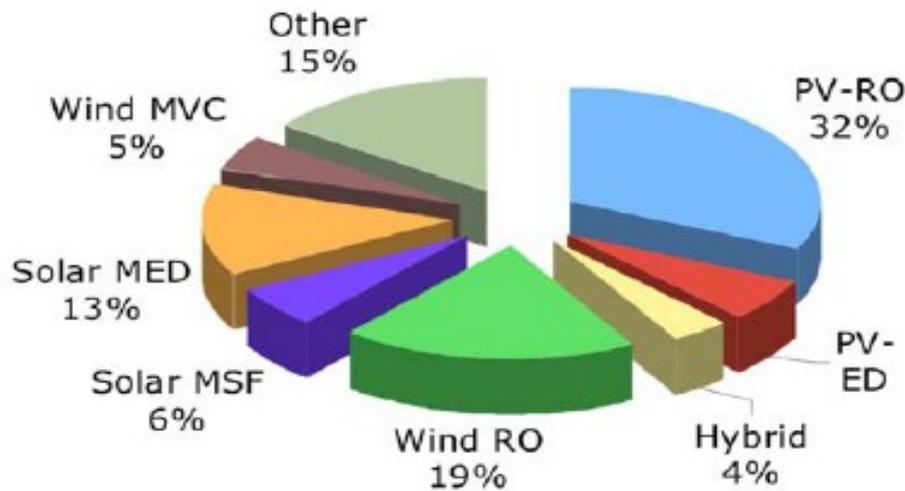


Fig.8. Distribution of Renewable-Powered Desalination Technologies [36]

7. Wind Power

The operating principle behind wind generators is the conversion of the kinetic energy of wind into electricity. The blades of a wind turbine capture this kinetic energy from wind to spin a rotor that can be used to generate electricity. The power of the wind (P) is determined by three variables: the density of air (ρ , in kilograms per cubic meter), the area of the windmill blades (A , in square meters), and the wind velocity (V , in meters per second). The relationship between wind power and these variables is given in the following formula:

$$P = \frac{1}{2} \rho A V^3 \quad (1)$$

As evidenced by this formula, wind speed has the greatest influence on determining potential wind power (wind power determined by the wind speed cubed - doubling the wind speed increases potential wind power by a factor of eight.)

Considering wind speeds (and directions) can be highly variable on differing time scales, designing wind generators that can withstand periodic gusts of high velocity winds is a critical aspect for the feasibility of wind power systems. Additionally, intermittent winds mean variable power production based on exogenous factors, which is a general criticism of the potential for expanding wind power generation.

Furthermore, it is important to note that while the formula above does provide a value for wind power, this is not the value of the wind power captured by the wind generator because the blades do not stop the wind completely (a necessary result of complete conversion of kinetic energy to electricity.) In 1919, Albert Betz, a German physicist, calculated the maximum wind power conversion potential of wind turbines to be 59.3%, known as the Betz limit. However, a recent study has shown that the Betz limit may have been an overestimation because Betz neglected to incorporate the curvature of fluid streams (such as air currents) into his calculations. This same study suggests that the practical conversion rate at maximum efficiency is closer to 30% for typical, horizontal-axis wind turbines [37].

In the 1970s, American engineers experimented with large, lightweight wind turbine designs, but their attempts generally failed as the machines were commonly destroyed by heavy winds [38]. In the mid-80s, Danish wind companies (such as Vestas Wind Systems) began to build heavier, more rugged models that have become the global standard for turbine designs [38]. A typical modern turbine has three blades on a horizontal axis, spanning 77 meters in diameter and capable of producing 1500 kW. Further technological advances have included computer systems that automatically adjust blade position and speed to produce electricity as efficiently as possible and also protect the turbine during high winds [39].

As mentioned above, the majority of modern wind turbines operate on a horizontal axis, but vertical-axis turbines can also be used. An advantage of vertical-axis turbines is that they do not have to be manually or digitally oriented towards the wind, but rather can utilize wind from any direction without adjustments. Additionally, some studies suggest that vertical-axis turbines have the potential to more efficiently convert wind power into electrical energy (35% conversion rate as opposed to 30% maximum for horizontal-axis turbines) [37].

Site selection plays a critical role in the viability of wind power production. The importance of wind speed was discussed as a critical determinant of wind power potential in a region. Not only does the local wind velocity need to be high, but it also needs to be somewhat consistent for a wind generator to be economically efficient. Therefore, having wind speed measurements throughout the year for many years is important data necessary for determining the viability of a wind power site.

In addition to consistent, high velocity winds, proper sites need to be relatively free of obstructions, such as: large buildings, forests, rocky cliffs, etc. A large obstruction can create a 200-300m "wake" that can reduce wind speeds at a downwind turbine by up to 10% [34]. Consequently, the potential for offshore wind farms becomes obvious as the coastal shelves provide a massive resource of relatively uninterrupted wind space.

8. Wind Energy and Reverse Osmosis

An important consideration for wind-powered desalination project design is whether to have an autonomous (off-grid) or grid-connected system. This decision will be heavily based on the local context, such that sites close to larger population centers can use grid energy as a backup to the renewable energy source. Alternatively, remote communities might not have any substantial electrical infrastructure, so a standalone system would be better suited for this type of environment.

An advantage of grid connection is that the desalination system can continue to operate in low winds, and can provide a more dependable supply of energy in general.

Additionally, the system could be set up so that any residual wind energy not used for desalination can be sold back to the grid, thereby lowering operational costs by generating operational revenue.

For autonomous wind-powered desalination, a power storage or backup generator may be required to continue operations in periods of reduced wind. This additional system is required because wind power varies with available winds, but most current desalination systems are currently designed to operate with consistent energy input [35]. An affordable and effective power storage system would be more desirable than a backup generator because residual wind energy could be conserved and used rather than introducing a system that requires fuel sources. In some cases, fossil fuel systems have been avoided by coupling wind energy with photovoltaic (PV) systems as an energy backup, but PV systems are also subject variable energy output [36]. In other words, in periods of low wind and low solar energy availability (nighttime) the desalination system would lack sufficient energy input.

However, as mentioned in the Emerging Technologies section below, there are currently designs that allow for variable energy input for desalination operation, thereby precluding the need for back-up generators and energy storage.

Regardless of the difficulties associated with intermittent power production, it seems that wind-power desalination represents a promising coupling of innovative technologies.

In fact, the intermittent nature of wind energy is uniquely suited for water-based applications (such as desalination and pumping) because the water can be processed and stored in periods of high winds and the water stored in reserve can be used during periods of low winds. Effectively, the water storage system acts as a battery, but with an efficiency of nearly 100%.

An additional study explores the relationship between renewable energy systems and desalination plants based on plant capacities. Table 4 below suggests that wind powered RO installations are recommended for small (1-50 m³/d) and medium (50-250 m³/d) capacities, but for larger capacities wind-powered vapor compression (VC) systems are recommended.

These results are somewhat puzzling given that VC units were identified as having significantly lower maximum production capacities (2,400 m³/d) than RO systems (128,000 m³/d). Table 6 above classifies anything greater than 250 m³/d as "large", so VC technologies can be considered as having a "large" capacity in this analysis. This suggests that the intermittent availability of wind production imposes a greater limit on RO units than VC units, and this makes sense considering that membranes are designed to work at a specific, optimal capacity [34].

However, given the flexible, modular structure of both technologies (membranes can be added to increase desalination capacity and turbines can be added to increase power capacity), it seems that there might be a greater potential for large-scale wind powered facilities than Table 6 suggests, especially in the context of any technological advances that address the intermittent availability of wind speed.

Table 4. Recommended Renewable Energy–Desalination Combinations [34]

Feed water available	Product water	RE resource available	System size			Suitable RE-Desalination combination
			Small (1–50 m ³ d ⁻¹)	Medium (50–250 m ³ d ⁻¹)	Large (>250 m ³ d ⁻¹)	
Brackish Water	Distillate	Solar	*			Solar distillation
	Potable	Solar	*			PV – RO
	Potable	Solar	*			PV – ED
	Potable	Wind	*	*		Wind – RO
	Potable	Wind	*	*		Wind – ED
Sea Water	Distillate	Solar	*			Solar distillation
	Distillate	Solar		*	*	Solar thermal – MED
	Distillate	Solar			*	Solar thermal – MSF
	Potable	Solar	*			PV – RO
	Potable	Solar	*			PV – ED
	Potable	Wind	*	*		Wind – RO
	Potable	Wind	*	*		Wind – ED
	Potable	Wind		*	*	Wind – VC
	Potable	Geothermal		*	*	Geothermal – MED
Potable	Geothermal			*	Geothermal – MSF	

An interesting synergy exists between the technologies in relation to coastal geographies. Clearly desalination plants processing seawater gain from being situated close to the water, both for easy access to feed water as well as easier disposal of the briny concentrate. While wind systems certainly gain from relatively consistent coastal winds, the real advantage comes from the recent development of offshore wind technologies. As mentioned previously, wind energy can be significantly reduced by the presence of large obstructions near a site. Offshore technologies allow the turbines to be located miles offshore, thereby reducing dramatically the presence of any potential wind dampening obstructions. A project in Denmark completed in 2002, involved the installation of 80 wind turbines (160 MW total) [40] between 14 and 20 km offshore and able to power approximately 150,000 Danish households [32].

9. Potential for Integrated Wind and Desalination

As mentioned above, the use of both wind power and desalination technologies are growing in absolute terms, as well as geographically. Meanwhile, the cost of implementing both of these technologies is decreasing. Additionally, the global population continues to grow, creating increased demand for both energy and water resources. Assuming all of these trends continue, it is likely that the integration of these two technologies will become an attractive option for increasing regional water supplies by producing freshwater from seawater. RO is a pressure-driven membrane separation process in which the water from a pressurized saline solution is separated from the solutes via diffusion across a semi-permeable membrane. The pressure required to drive the separation process is dependent on the resistance of the membrane and on the saline concentration of the water. An overview of the RO system and its major components is shown in Fig. 9. Pretreatment is critical to ensure membrane surfaces remain clean to maintain performance and reduce fouling or degradation. Therefore, suspended solids are removed via

filtration. Typically, pretreatment also consists of fine filtration and the addition of acid or other chemicals to inhibit salt precipitation and microbial growth.

Finally, chemical addition is also utilized to ensure pH and alkalinity levels are within a specified range corresponding to membrane manufacturer’s requirements. An RO system consists of multiple pressure vessels that are connected in parallel, and each closed vessel consists of multiple elements in series. Since the feedwater input at each closed vessel is approximately equivalent with regard to pressure and flow rate, the performance of the overall system can be ascertained by the performance of a single vessel. The permeate is post treated to stabilize the water for distribution. Since the pressure drop in an RO system is small, the brine concentrate has significant pressure energy, which if recovered can improve overall system efficiency. For all the parts of the system, physical and economic models have been built in order to allow a detailed study of the system behavior both in steady state as in transient conditions. These models also included constraints of the current equipment that might limit the design space. A large variety of sensitivities has been studied.

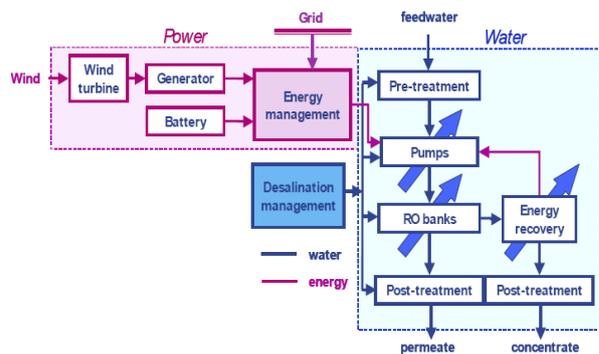


Fig. 9. Components of system model for wind-powered RO. [41]

It is evident that the water production of a wind powered desalination system depends on the power available. For the RO system, this dependency can be seen in Fig. 10. Under optimum conditions, such a system designed for a 1.5 MW turbine is capable of producing up to 5500 m³/d.

The annual average wind power density was calculated from the measured speeds of eleven stations distributed all over the country. These stations include Amman, Um Ejmal, Fujaij, Ibrahimyya, Maan, Hofa, Kamsha, Aqaba, Tafila, Al-Reeshah and Al - Harir; the annual average wind speed of these locations is shown in Figure 11. The annual wind speed of six locations is above 7 m/s. Their power outputs vary within the range of 66 to 244 Kw. The produced power based on the available wind speed of these locations is shown in Figure 12. The water produced is 1690 m³/day, 1744 m³/day, 1635 m³/day, 2660 m³/day, 1537 m³/day, and 3074 m³/day for Hofa, Kamsha, Aqaba, Tafila, Al-Reeshah and Al-Harir, respectively.

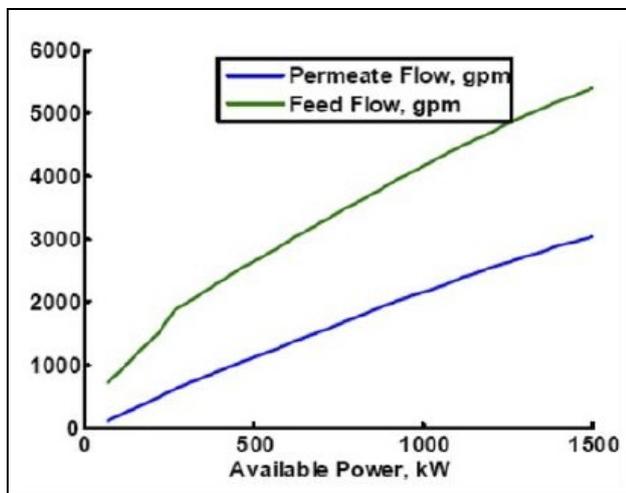


Fig. 10. Product yield depending on wind power available [41]

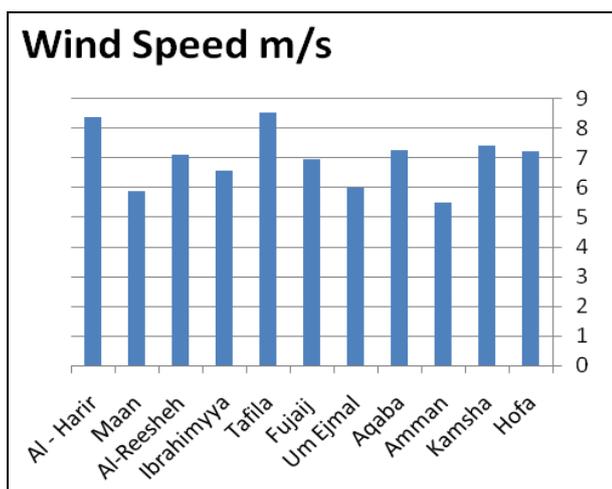


Fig. 11. Wind speed at different locations in Jordan

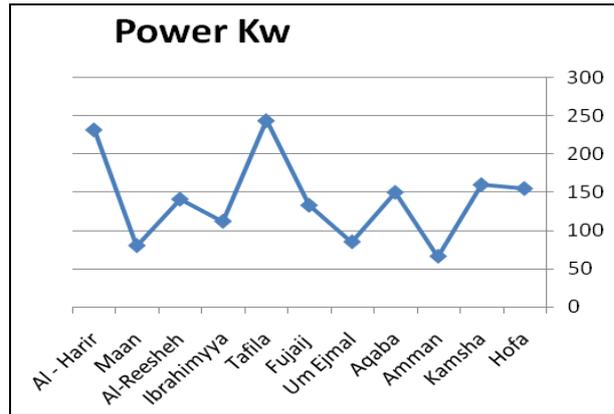


Fig. 12. Produced wind power based on wind speed

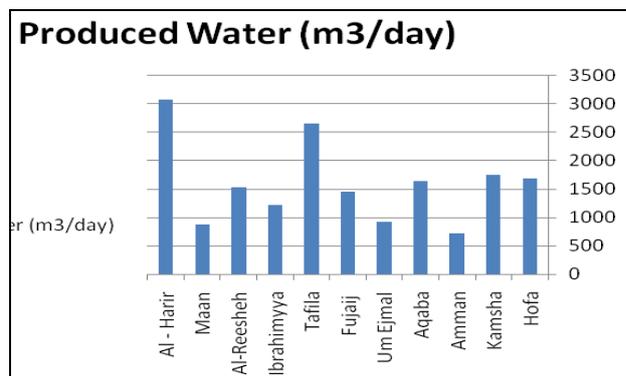


Fig. 13. Product yield at specific locations depending on wind power available

10. Cost Analysis

The cost effectiveness of wind generators is primarily influenced by the wind resource availability of a proposed site and the economic parameters that influence capital costs [34]. As mentioned above, available wind power depends mainly on the local wind speed; more electricity can be produced in areas with consistent, high-velocity winds. Wind generators tend to have high initial capital costs, but low operating costs because of the lack of fuel costs. Therefore, the economic parameters related to the cost of capital and interest/discount rates are significant variables in the cost calculations. Costs less than US \$0.05 per kWh have been achieved for some grid-connected wind generators, and costs of approximately \$0.03 per kWh are projected for a wind installation in Scotland in a region that has consistent, high-speed winds [34]. Neither of these cost estimates includes the cost of power storage, which would significantly increase the estimates. These costs continue to decrease as advancements are made in the design technology and the sector continues to grow and gain from economies of scale. By one estimate, manufacturers of heavy-duty wind turbines have reduced costs fourfold since 1980.

Table 5 provides cost estimates of wind power and other renewable energy sources as compared to nuclear energy and fossil fuels. Onshore wind systems cost about 3 to 5 cents per kilowatt hour (kWh) and offshore wind systems are double the cost at 6 to 10 cents/kWh. However, these costs are projected to drop by 2020 to approximately 2 to 3 cents/kWh. Fossil fuel costs are estimated at 2 to 4 cents/kWh for natural gas and 3 to 5 cents/kWh for coal. It is likely these costs are underestimated considering the costs of fossil fuels rose dramatically in the last

year (the price of a barrel of oil hit an all-time high of \$70.85 in August 2010). Furthermore, these estimates for fossil fuels most likely do not include externality costs associated with fossil fuel dependent systems, which may include the health costs from particulate air pollution and costs associated with greenhouse gas emissions and climate change. Additionally, countries without oil reserves such as Jordan are forced to import oil, thereby spending valuable foreign exchange for ongoing energy costs. With an operational wind sector, it is possible for a country to not only reduce dependence on foreign oil, but also export wind-generated electricity to neighboring countries. Wind speed, and subsequently potential for wind power production, is not evenly spread around the world. Wind turbines can only be cost effective in areas where there is sufficient wind speed to produce significant electrical

or physical (shaft) power. It is understood that wind speeds of Class 3 and above (greater than 6.9 meters per second, m/s) at 80 meters of altitude are sufficient for the low-cost production of wind power. Therefore, the next restriction will be to remove potential wind sites that have wind speed estimations of less than 7 m/s. This indicator of the global wind power potential data layer is not determined spatially, so a simple selection by data attribute can remove all data points with wind speed measurements less than 7 m/s. This operation can be accomplished using the data attribute table in MapInfo, so that data points can be selected to create a new map that will show only the wind measurement sites within 25 km of the coast and demonstrating wind speeds greater than or equal to 7 m/s.

Table 5 Costs of Renewable Energy Compared with Fossil Fuels and Nuclear Power [40]

Technology	Current cost (U.S. cents/kWh)	Projected future costs beyond 2020 as the technology matures (U.S. cents/kWh)
Biomass Energy:		
• Electricity	5-15	4-10
• Heat	1-5	1-5
Wind Electricity:		
• Onshore	3 - 5	2-3
• Offshore	6 - 10	2-5
Solar Thermal Electricity (insolation of 2500kWh/m ² per year)	12-18	4-10
Hydro-electricity:		
• Large scale	2-8	2-8
• Small scale	4-10	3-10
Geothermal Energy:		
• Electricity	2-10	1-8
• Heat	0.5-5.0	0.5-5.0
Marine Energy:		
• Tidal Barrage (e.g. the proposed Severn Barrage)	12	12
• Tidal Stream	8-15	8-15
• Wave	8-20	5-7
Grid connected photovoltaics, according to incident solar energy (insolation):		
• 1000 kWh/m ² per year (e.g. UK)	50-80	~8
• 1500kWh/m ² per year (e.g. southern Europe)	30-50	~5
• 2500 kWh/m ² per year (most developing countries)	20-40	~4
Stand alone systems (incl. batteries), 2,500 kWh/m ² per year.	40-60	~10
Nuclear Power	4-6	3-5
Electricity grid supplies from fossil fuels (incl. T&D)		Capital costs will come down with technical progress, but many technologies largely mature and may be offset by rising fuel costs
• Off-peak	2-3	
• Peak	15-25	
• Average	8-10	
Rural electrification	25-80	
Costs of central grid supplies, excl. transmission and distribution:	2-4	Capital costs will come down with technical progress, but many technologies already mature and may be offset by rising fuel costs
• Natural Gas	3-5	
• Coal		

11. Conclusions

The use of both wind power and desalination technologies are growing in absolute terms, as well as geographically. Meanwhile, the cost of implementing both of these technologies is decreasing. Additionally, the global population continues to grow, creating increased demand for both energy and water resources. Assuming all of these trends continue, it is likely that the integration of these two technologies will become an attractive option for increasing regional water supplies by producing freshwater from brackish and seawater.

Furthermore, the availability of powerful winds is clearly necessary for a wind power station to be economically effective.

According to our analysis, Jordan has few potential "hotspots" for the implementation of wind-powered desalination, these areas include Hofa, Kamsha, Aqaba, Tafila, Al-Reeshah and Al – Harir; all average wind speed is above 7 m/s. The water produced is 1690 m³/day, 1744 m³/day, 1635 m³/day, 2660 m³/day, 1537 m³/day, and 3074 m³/day for Hofa, Kamsha, Aqaba, Tafila, Al-Reeshah and Al-Harir, respectively.

It is recommended to use advanced technology such as geographical information systems (GIS) to identify wind-powered desalination hotspots because it allows the user to perform analyses based on spatial reference data.

Acknowledgments

The Author would like to acknowledge the support of the Hashemite University during his sabbatical leave; this research was carried out during this period.

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