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Design Proposal for a Renewable Energy Powered Desalination System

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EXECUTIVE SUMMARY

The Kingdom of Jordan is the 10th water poorest country in the world and the 4th water poorest country in the Middle East. The natural water resources of the country are not sufficient to meet the demands of the population and because of this water rationing has been in place since the 1980's. Currently, the economically viable harnessing of surface water has been maximized, groundwater is being pumped at 160% of the sustainable yield, and non-renewable fossil water is also being utilized. A rapidly growing population and industrial sector threaten to exacerbate the water shortage in the very near future. Jordanian scientists in partnership with international organizations have determined that desalination of saline water will play the most important role in alleviating the country's water scarcity problems. This document will outline a design proposal for a desalination unit to be powered by a renewable energy source that will provide sufficient fresh water for the needs of a small rural community in Jordan.

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INTRODUCTION

There are many issues related to water that nations are struggling with in the 21st century. Currently, about one quarter of the world's population, or about 1.2 billion people, lacks access to sufficient water of good quality (Rijsberman, 2005). This problem is only exacerbated as the world population continues to climb, as it has been shown that water usage increases at twice the rate of population increase (Eltawil et al., 2009).

"Since 1950, global water use has tripled and in the next twenty years, it is estimated that humans will require 40% more water than we currently use [in 2000] (Eltawil et al., 2009)." Consequently, water scarcity, lack of accessibility, water quality deterioration, and insufficient recharge of ground water and over extraction of fresh water are all increasing in severity as economic growth leads to population growth and which requires ever-expanding irrigation for highly productive agricultural systems. This shortage of water is a serious threat to world peace and security in the near future (Eltawil et al., 2009).

Actions taken to alleviate water scarcity can be grouped into three categories: preservation of the quality of current supplies, increasing efficiency of current water usage, and increasing the overall quantity of available fresh water (Eltawil et al., 2009). Methods undertaken to accomplish these goals include desalination of saline water, rainwater harvesting, wastewater reuse, and water importation (Jaber et al., 2001).

Water issues are especially severe in the Mediterranean basin, southern Europe, the Middle East, Asia and Africa where there is a condition of physical scarcity of water. Very large portions of the people stricken by water shortages are those who live in remote rural areas, where the socio-economic conditions prevent the rapid implementation of water treatment technology (Rijsberman, 2005). Undeveloped rural regions without access to the electrical grid typically do not have access to the infrastructure required for large scale desalination plants nor the need for such facilities. Consequently, there is an apparent need to develop desalination technology which will function off-the-grid and on a smaller, village scale.

Fortunately, island nations suffering from salt water intrusion typically have high wind resources. The arid and semi-arid regions of the world are also some of most solar-resource rich areas, which make sense, because the driest areas tend to have increased in solar irradiation because of their proximity to the equator. Under these conditions, the coupling of a renewable energy system (wind power, solar thermal, geothermal) to the desalination process makes water treatment feasible in remote areas. (Eltawil et al., 2009).

1. PROBLEM IDENTIFICATION

In countries with a high population growth rate and fast socio-economic development, water demand and wastewater production is steeply increasing and the gap between water supply and demand is getting wider. Fortunately, efficient technologies have been developed to treat wastewater and brackish water desalination for communities where fresh water is scarce. A number of such communities in arid regions have turned to desalination technologies because of it being a relatively feasible alternative for fresh water production.

Jordan's population reached 5.3 million in 2002 and continues to grow at an annual rate of 3.6%. This is a very high rate of growth when compared to Canada's 1.1% population growth rate (Statistics Canada). Annual rainfall ranges from 600mm in the highlands of North-western Jordan to 130mm or less in the deserts in the East and South, which make up 91% of the surface area of the country. This is a very small amount of precipitation when compared to Canada's range of 250 mm in the far North to over 900mm in the Atlantic Provinces. Due to very high evaporation rates in the Jordan, 85% of the rainfall is lost to the atmosphere. Of the remaining 15%, 4% goes towards the recharge of groundwater and the other 11% is equal to available surface water (Mohsen, 2007).

Jordan has three main sources of surface water, the Zarqa (Jakkob) and Yarmouk Rivers, which both drain westward to the Jordan River and eventually to the Dead Sea. The Jordan River forms the border between Palestine and Jordan while the Yarmouk River forms the border with Israel in the Northwest, to the South of the Sea of Galilee (Lake Tiberias). Farther upstream and to the Northeast, the Yarmouk also serves as the border between Jordan and Syria.

The Zarqa River water system is becoming increasingly polluted from the industrial area around the Zarqa-Amman region, where 70% of Jordan's industry is located, and its ability to provide clean water has been greatly diminished. Syria has built a number of dams on the Yarmouk in order to divert water for its own purposes. Perhaps an even greater strain on the surface water resources for Jordan has been the construction of the National Water Carrier by Israel in 1967, which takes water from upper Jordan River at Lake Tiberias. The construction of this project has significantly reduced the flow of the lower Jordan River (Mark Zeitoun). Unfortunately, Syria and Israel have taken advantage of their upstream riparian position without regard for Jordan's fair share of the water available from sources shared by all three countries (Mohsen, 2007).

Jordan's conflict with Israel was in part due to the issue of unfair water sharing practices. In 1994, Jordan and Israel signed a peace treaty which guaranteed an additional 215 million cubic meters (MCM) of water for Jordan through new dams, diversions, pipelines, and desalination plants. Even with this improvement, Jordan is still a very water poor nation.

Jordan has one of the world's lowest per capita water resources. Water scarce countries are defined as having access to less than 1000 m^3/year per capita. In 1996, Jordanians consumed an average of less than 175m^3/year per capita. In 1997, a total of 882 million cubic meters (MCM) of water was used in Jordan. Of this total, 225 MCM exceeded the sustainable groundwater yield and an additional 70 MCM was sourced from non-renewable fossil water. Fossil water is groundwater that was accumulated during a time of a dramatically different climate in the region and that has been sealed by geological processes for thousands of years. Without an increase in overall availability of water and a constant population growth rate, the per capita consumption of water could drop down to 91m^3/year by the year 2025 (Mohsen, 2007).This would relegate Jordan to absolute water scarcity status, the most severe level of water scarcity, recognized by the UN to be less than 100m^3/year per capita (Rijsberman, 2005).

It is also important to note that continual over-extraction of groundwater undermines the sustainability of these already limited water resources to provide fresh water into the future. Groundwater resources are being exploited for 160% of their sustainable yield. In some regions, over-extraction has lead to a 5 meter drop in water levels and a tripled salinity. If current trends continue, some of these over-exploited basins will run dry within the next few years. Dropping water table levels as well as the increasing salinity of groundwater are the direct result of over-extraction and imply increasing scarcity and a higher cost of fresh water in the future (Mohsen, 2007).

There are a number of factors which exacerbate the issue of water shortage in Jordan. The low availability of fresh water that can be pumped economically, in combination with large influxes of refugees and a rapidly growing population, improving standards of living, as well as the geo-political situation in the region are some of the factors that have caused the current condition of water scarcity in the region. Wastewater treatment plants operating beyond design capacity are becoming a significant source of pollution for groundwater as well. Inefficiencies in Jordan's irrigated agriculture systems have caused 70% of available water to be allocated to the agricultural sector. Increased effectiveness in irrigation will play an important part in freeing up more water for the growing domestic and industrial needs of the country. In addition, because the Kingdom of Jordan's priority is to provide potable water for domestic use, water resources will be allocated away from agriculture and towards the domestic and industrial sectors. This makes sense economically "since the product value of 1 m^3 of water consumed in industrial production is very much higher than for the same amount consumed for irrigating wheat fields or orchards. In Jordan, for example, productivity per unit of consumed water is 40 times higher in industry than in agriculture, and employment effect is 13 times higher" (Mohsen, 2007). For arid countries, the optimization of water use may imply that increased importation of food from nearby regions is necessary.

Though Jordanians currently consume about 175m^3/year per capita, domestic usage of water accounts for only 20% of the total and roughly amounts to 96L/day per capita. According to the UN, 100L/day per capita is the minimum requirement for a settled population to have proper sanitation and a reasonable standard of life. These figures shed light on the severity of the water crisis in Jordan, as unsustainable pumping of water resources is already occurring in order to keep quality of life at an adequate level. Access to water is highly limited to all sectors of the country and especially so during the summer months of May-September, during which absolutely no rain falls. During this time, the capital city of Amman has water access for a few hours once every seven days and rural areas receive a delivery of water once every twelve days (Denny et. al, 2008)

2. OBJECTIVES AND SCOPE

Jordan's water shortage needs to be addressed quickly before very serious environmental and social problems arise. Because of the unreliability and inefficiencies incurred in the transport of treated water over long distances to remote communities in Jordan, we propose to complete a system design for a small scale desalination unit powered by a locally abundant source of renewable energy which can economically bring water autonomy to an otherwise disenfranchised group of people.

Within the scope of this project will be the selection and sizing of an appropriate:

- Desalination unit
- Renewable energy system (including energy storage)
- Pre/post-treatment unit
- Associated machinery (pumps, storage tanks, etc.)
- Brine disposal system

Additionally, a cost evaluation of the designed system will be performed to ensure feasibility of implementation of this design and to show that alternative energy combined with appropriate small scale desalination technology is cost-competitive with large desalination plants powered by conventional sources.

3. LITERATURE REVIEW

3.1. DESALINATION TECHNOLOGIES

When we talk about desalination technology, we first need to define it as a separation of saline water into two main streams:

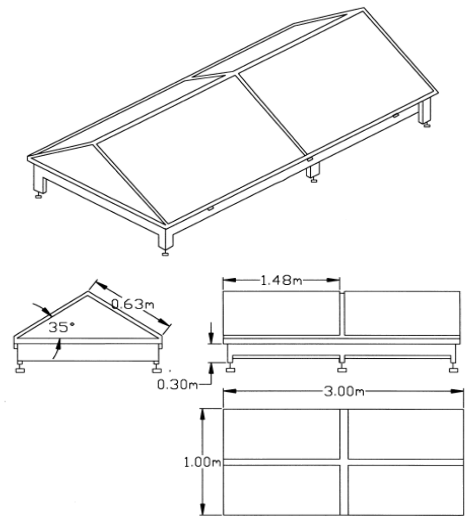
- the fresh water (<500 ppm total dissolved salts) (Afonso et al., 2004)
- the remaining of the solution or the dissolved salts, which is called brine water

There are two basic processes for desalination: Thermal distillation uses thermal energy to induce a phase change that separates water vapor from the dissolved salts. The second method is membrane separation which uses a pump to force the solution through a semi-permeable membrane, overcoming the osmotic pressure necessary to separate the fresh water from the brine (Eltawil et al., 2009).

Solar Still

As an introduction to the desalination technologies the Solar Stills are the simplest system of all. Solar distillation is a proven technology for water desalination. Systems can be sized for one person, up to community sized systems. They have no moving parts, relying only on the sun for energy. The mechanism of a solar still starts when solar energy is allowed into the collector to heat the water. The water evaporates only to condense on the underside of the glass. When water evaporates, only the water vapor rises, leaving contaminants behind. Illustrated in Figure 1, the gentle slope of the glass directs the condensate to a collection trough, which in turn delivers the water to the collection bottle.

Figure 1: Solar still schematic (Akash, 2000).



The major advantage of the basin still is that it does not require a pressurized water supply to pump the feed water into the still. In addition, it could be mobile and thereby very easy to handle and maintain. On the other hand, it is susceptible to weather damage and requires large areas of land for installation for a community size system. They have low output (12L/m2/day) (Farid et al,. 1996). In addition the material is expensive relative to the production rate.

Reverse Osmosis (RO)

Reverse Osmosis is the most widely used desalination technology around the world. RO involves applying high pressure to force the water to move from a more concentrated solution to a weaker one. The semi-permeable membrane allows water to pass through, but blocks the passage of the bulkier salt molecules. As a result, fresh water is accumulated on one side and brine on the other. The main advantage of this system is that reverse osmosis process is used in cases where water is high in salinity (from 500 to 50,000 ppm) and allows a good removal of solids and bacteria. On the other hand, the membrane is sensitive to bio-fouling and any excess total suspended solids; hardness and turbidity in the water will cause scaling on the surface of the membrane and therefore reduce the quality of water in the end as well as the volume of water filtered. Also the system requires a good pre-treatment to produce potable water (Eltawil et al, 2009).

Electrodialysis (ED):

It is a less popular type of membrane separation, developed 10 years before RO system. It uses an electric current to draw dissolved salts and metal ions through a selective membrane, leaving behind fresh water. It can be used for desalination of brackish water at a small (1-50m^3/d) or medium (50-250m^3/day) scale and requires an energy input of 0.5–2.5 kWh/m^3. 85-94% of water can be recovered with total dissolved solids content of 140-600mg TDS/L. The energy consumption is a proportional to the amount of salts removed, not the volume of water treated therefore making the system more efficient for less saline feed water. In addition, ED has been shown to be a good match for wind energy because it can handle variability in power input by changing the flow rate through the membranes. However, typical systems of ED can only handle brackish water (up to 12,000 mg TDS/L). Also, periodic cleaning of membranes is required or it may develop leaks in the stack of membranes. Post-treatment for bacteria is needed to produce potable water (Eltawil et al., 2009).

Nanofiltration (NF):

NF can be used as a pre-treatment system. It is a relatively new membrane separation technology that is beginning to compete directly with RO and ED systems. Nano-filtration units can be designed with different membrane qualities and typically have pores smaller than 1 nanometer. The advantage of NF is that it can remove organic chemicals, herbicides, pesticides, detergents, and viruses. These abilities make it a good pre-treatment system for desalination but it cannot operate on its own for the same process since it is a pre-treatment (Diawara, 2008.).

Mechanical Vapor Compression (MVC) and Thermal Vapor Compression (TVC):

Vapor compression is another distillation process. After saline water is heated by an auxiliary heat element in the boiling chamber the generated vapors are compressed, thereby increasing pressure and temperature of the steam. The compressed steam is routed back through the boiling chamber via a heat exchanger on which the steam condenses and releases the latent heat back to the boiling liquid, recycling the energy. The condensation of the steam results in the production of very hot distilled water, which pre-heats the saline feed water entering the system while cooling the final product and increasing energy recycling within the system. This system can use either a mechanical source of energy (shaft power) or electrical energy to run the compressor and thermal power to heat the feed water. This process has low consumption of chemicals, relatively low energy input and is considered to be a portable design which allows flexibility. However, the system requires an auxiliary heat source for start-up and the compressor itself requires a lot of maintenance in order to operate economically and efficiently (Eltawil et al., 2009).

Multi-Effect Distillation (MED):

MED is a multi stage distillation process very similar to MVC. This process uses an external steam supply to heat the saline water. The operation is done at low temperatures (70^{o}C), thereby making it more energy efficient than other multi stage distillation processes. A vacuum pump is used to lower the pressures in the vacuum chamber and the sea water is heated until it vaporizes. The vapors generated in one stage are used as the heat source for each subsequent lower pressure stage in the process. Some of the sea water vapor condenses and is removed as fresh water during each stage. The electrical power requirement is 2.5-2.9 kWh/m^3. The thermal power requirement is 4.5-6.5 kWh/m^3. In addition up to 65% of the water can be recovered as fresh water and the final product has less than 10 mg TDS/L. Furthermore, the process requires minimal pre-treatment and little operator input. In addition, heat and electricity can be cogenerated to increase efficiency of production for the MED system. However, this will result in high energy consumption, high capital and operational costs and because of this the system can only be economically feasible on a large scale. The system requires good quality material to avoid corrosion problems in the piping and overall system configuration (Eltawil et al., 2009).

3.2 RENEWABLE ENERGY TECHNOLOGIES

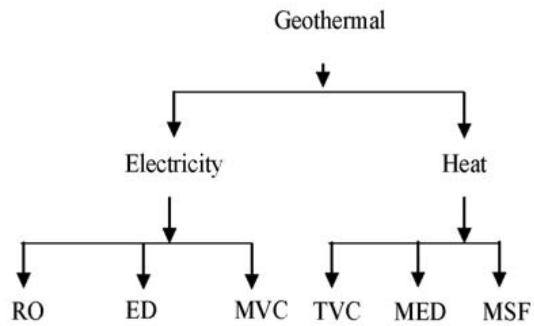
Renewable energy technologies offer an excellent source of power for the desalination process in regions where fossil fuels are prohibitively expensive or are inconsistently available. Renewable energy technologies have steadily become more available, reliable, and affordable since their introduction. Rising fuel prices and concerns about pollution from the combustion of fossil fuels are also making renewable energies ever more competitive in the marketplace. Additionally, the implementation of local energy resources to power the desalination process can lead to water and energy autonomy and consequent improvements in social conditions for the community under consideration (Eltawil et al. et al., 2009). The following section contains a review of mature, commercially available renewable energy technologies:

GEOTHERMAL

Geothermal power is extracted from heat that is stored within the Earth. Geothermal energy systems are essentially heat pumps which function on the temperature difference between ambient surface temperatures and the higher temperatures that are prevalent deep below the surface. Because temperatures within the Earth are relatively stable, these energy systems are able to provide a continuous and reliable power output. Geothermal heat pumps are usually part of a thermal power plant, in which the extracted heat is used to drive vapour generation for steam turbines. This arrangement makes geothermal energy well suited for the cogeneration of heat and electricity, which greatly increases the efficiency of the operation.

Although geothermal energy generation is highly efficient, applications are highly limited by location to sites where the heat source is close to the surface of the Earth so as to minimize drilling, which is very expensive at great depths. In locations where this source of energy has been harnessed, MED units have been determined to be the best desalination technology match, although others are possible, because MED units require the direct and continuous source of thermal energy that geothermal energy systems can reliably provide (Eltawil et al., 2009).

Figure 2 below shows all of the potential desalination technology combinations for geothermal energy.



SOLAR

Geographically-speaking, there are often abundant solar resources in regions with a need for desalination installations. This is because arid regions with few water resources tend to be closer to the equator where incident solar radiation is the highest on the surface of the Earth.

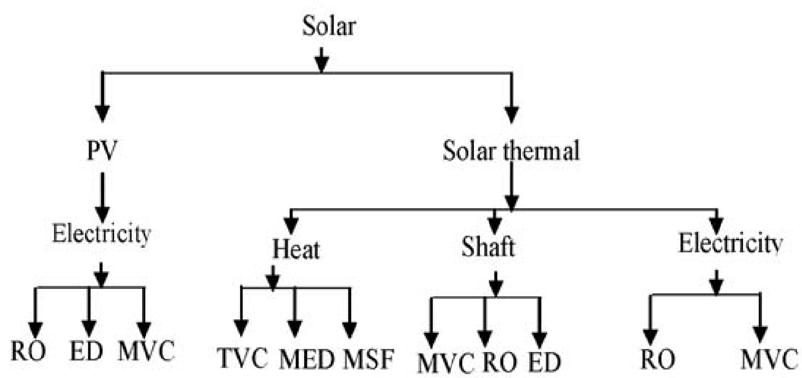
The output of solar energy systems tends to be relatively unpredictable and intermittent and because of this condition, typically requires an energy storage unit in order to ensure continuous operation of solar energy driven machines.

Solar energy technology can be divided into two general categories: solar thermal and solar electric.

Solar thermal refers to the collection of solar energy as heat. Low and medium temperature systems are flat plate collectors with a large number of tubes encased in a transparent plastic enclosure. The transparent plastic creates a greenhouse effect and the trapped heat is then transferred to the working fluid which has a high heat capacity. High temperature systems use reflectors to concentrate solar energy in order to generate water vapours to power a steam turbine. While these systems are highly efficient, the application of concentrated solar power for electricity generation is somewhat restricted to large scale installations. These systems can be used as a direct source of thermal energy for distillation processes. Thermal energy can be stored in large masses of concrete, ceramics, or other such media (Eltawil et al., 2009).

Solar electric refers to the generation of electricity from solar energy. Although solar electric power has a higher cost per kWh (see Table 1), it has been repeatedly proven that it is well-mated to membrane distillation processes such as RO and ED. The reason for this is because they require a lot less power than other desalination technologies and also can handle some variability in power by varying flow rate across the membrane (Abu-Jabal et al., 2001., Abdallah et al., 2005., Hasnain et al., 1998., Hrayshat, 2008., Mahmoud, 2001., Mohsen et al., 2001). Electrical energy generated from solar photovoltaic arrays can be reliably stored in batteries (Eltawil et al., 2009).

Figure 3 below shows all of the potential desalination technology combinations for solar energy.



WIND

Wind energy resources are highly location-dependent and are typically abundant on islands and in coastal and mountainous areas. Like solar energy, the output of wind turbines is also intermittent and variable. Wind energy can be used directly as mechanical (shaft) power or used to generate electricity, which can be stored in batteries.

Mechanical power from wind energy has been shown to successfully run the compressors in a Red Sea-sited vapour compression desalination process (Karameldin, 2002). Electrical power from wind can be used to power both the compressor and the heating element in the vapor compression process as, to run the pump in the reverse osmosis process (Eltawil et al., 2009). It has also been successfully mated to an electrodialysis desalination unit (Veza, 2001).

Figure 4 below shows all of the potential desalination technology combinations for wind energy.

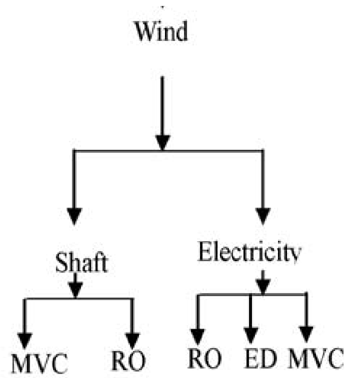


Table 1: Comparison of energy costs from various sources (Eltawil et al. et al., 2009).

Technology	Avg Current cost (US cents/KWh)
Wind Electricity	
onshore	4
offshore	8
Solar Electric PV	50
Solar Thermal	15
Geothermal Energy	6
Electricity Grid - fossil fuels	
Average	9
Rural Electrification	52.5
Nuclear Power	5
Natural Gas	3
Coal	4

3.3 PRE AND POST TREATMENT TECHNOLOGIES

Pre-Treatment

For the protection of the effectivity and life span of our Reverse Osmosis (RO) installation, a sufficient pre-treatment is required. It is said that an appropriate selection of pre-treatment methods for feed water will improve productivity and extend the life span of the system by preventing or minimizing bio-fouling, scaling and membrane plugging.

To perform a continuous and reliable pre-treatment of the feed water a special approach is used. A pre-treatment that is not proper to the installation may cause a system overload. When this occurs the system parts need cleaning much more often to restore productivity and salt retention. Cleaning costs, system performance and standstill time are very significant in that situation. The type of pre-treatment system that is used significantly depends on feed water quality. Consequentially, sufficient feed water pre-treatment is dependent on:

· The source of the feed water
· The composition of the feed water
· The function of the feed water

Slow Sand Filter

Before entering the desalination system, the raw water will pass thru a slow sand filter and a cartridge filter to remove surplus of turbidity (by biological action) and suspended solids, which may cause problems in pump operation and instrumentation if they enter the RO system. In addition, they may obstruct the flow channel or deposit on the membrane surfaces causing alteration in the quality of water and salinity. The water is filtered by the sand itself and by the layer of microorganisms that develops on top of the sand. First, a layer of dirt, debris, and microorganisms builds up on the top of the sand. Slow sand filters work through the formation of a gelatinous layer or bio-film in the top few millimetres of the fine sand layer. The bio-film is formed in the first 10-20 days of operation (Centre for Affordable Water and Sanitation Technology, 2007). The complex biological surface layer known as the bio-film consists of bacteria, fungi, protozoa, rotifera and a range of aquatic insect larvae. The water produced from a well-managed slow sand filter can be of exceptionally good quality with 90-99% bacterial reduction (National Drinking Water Clearinghouse, 2000).

The advantage of using the slow sand filter is that it does not require any use of flocculants or chemicals to work effectively. The slow sand filters can produce very high quality water free from pathogens, taste and odour without the need for chemicals. Passing the raw water through a slow sand filter removes the flocs and the particles trapped within, reducing the numbers of bacteria and removing most of the solids. After the sand layer, the water will move thru a mass of gravel and perforated pipes and/or a nylon curtain or a good geo-textile liner below the sand, limiting the infiltration of the sand into the RO feed pump. As a solution the sand filter may include a layer of activated carbon below the gravel layout in order to remove taste and odour.

Maintenance of the Sand Filter

Sand filters become clogged with floc after a period in use so they should be backwashed or pressure washed to remove the floc. Inadequate filter maintenance has been the cause of occasional drinking water contamination. Thereby, maintenance of the slow sand filter consists of gathering or raking the sand periodically and cleaning the filter by removing the top two inches of sand from the filter surface. After a few cleanings, new sand must be added to replace the removed sand. Cleaning the filter removes the bio-film and after cleaning the filter, the new filtration process must be operated for two weeks, with the filtered water sent to waste, to allow bio-film to rebuild itself. As a result, treatment plants must have two slow sand filters for continuous operation. Slow sand filters are very reliable filters which do not usually require coagulation/flocculation before filtration. However, water passes through the slow sand filter very slowly. As a result, large land areas must be devoted to filters when slow sand filters are part of a treatment plant. A careful periodic inspection of filters and pipelines can also be useful.

Cartridge Filters

As for the filtering applications, the choice of using the cartridge filter is a critical one since it is a sediment filter, that is to say it reduce the amount of sediments transported by the fluid trough filtration. The choice of cartridge filter will depend on the application. The cartridge filters are preferable for systems with low contamination. The cartridge filters as illustrated in figure 3 are also called surface filters. They will work best for our design since it has more surface area to filter sediment of very small size mainly less than 5 microns. Cartridge filters are normally designed to be disposable, therefore when they are clogged they will need to be replaced in order to maximize higher flows and have a better dirt holding capacity.

Post Treatment

Once the water has been filtered by the pre-treatment method and further by the Reverse osmosis system, there are two methods of post treatment for our project. First we could add chlorine to the product water in order to eliminate any residual bacteria that have bypassed the desalination process into the final product. The second post treatment possible is the use of Ultraviolet light. Disinfection may be by means of ultraviolet radiation, using UV lamps directly on the product water for the same purpose of eliminating the bacteria. In addition to the Ultraviolet radiation method, we could use the supplemental electricity that has been generated by our PV to feed the UV lights. Furthermore, after chlorination, the problem of the desalinated water being very corrosive on the cement or concrete lined surfaces, can be fixed by the use of a pH adjustment chemical or mineral such as lime will be important in order to stabilize, to protect downstream pipelines and storages tanks from corrosion. Liming material is used against corrosion but also to re-mineralise the treated water in order to meet the potable water. The RO permeate water will be stored in an intermediate tank. This potable water will be then pumped to another cartridge filter in order to eliminate any remaining sediments. The pure water flows from the modules to a storage tank.

3.4 BRINE DISPOSAL METHODS

In any type of desalination technologies, there is a production of concentrate brine (the concentrate stream which contains a high percentage of salts and dissolved minerals.). In most cases, desalination plants discharge their brine content back into the sea if they are located in coastal regions or underground if they are located inland. As we know, reductions in water quality and quantity have serious negative impacts on ecosystems. Due to the high level of salinity and its total alkalinity, brine can alter the temperature with of its surroundings both in the sea or ground water if not disposed of properly. Brackish water reverse osmosis concentrate, if discharged to surface water, can change the salinity of the receiving water. The change in salinity can change the concentration of dissolved oxygen in the water and negatively affect aquatic life; the standard limit for surface water discharge is a salinity difference of less than 10%. These impacts could be important in terms of the influence it has on the marine organisms, such as the development and survival of larva. The major concern of these impacts surrounds the outfall of the brine discharge because of its physical and chemical features (Mickley, 1993).

Therefore, the issue of utmost importance is eliminating these possible negative impacts on the environment by the development of cost effective brine disposal systems, which conform to regional and federal environmental constraints. The major strategies for brine disposal at inland sites are reduced to three general categories; 1) Deep Well injection 2) Solar Ponds 3) Evaporation Ponds. Other systems such as irrigation of salt tolerant plants (halophytic crops) , and recovery of inorganic salts for potential commercial value has also been suggested, however, they are costly to implement and do not demonstrate economic viability. The use of saline water for crop irrigation also adds salt to the soil and to the local groundwater aquifers (Mickley, 1993). Build-up of salt in the soil can affect future crop growth, while the groundwater will slowly increase in salinity over time. In addition, high boron concentrations in the irrigation brine water can cause plant damage (Nadav, 2005).

As a result this report will focus on a review of the three technological features for handling the volume of waste brine and one of which will be most cost effective and feasible for our project.

Deep Well Injection

This method is applied worldwide for disposal for land based industrial municipal and liquid hazardous wastes. Injection wells may vary in depth from few hundred feet to several thousand feet depending on the geological site location. This method is used as a model for any concentrate where inadequate waste solution transport and confinement could result in contamination of surface and ground water resources. Deep injection wells can be used to inject liquid wastes in porous subsurface rock formations. Site selection is dependent upon geological and hydro geological conditions. The use of this technology is not feasible in areas vulnerable to earthquakes or regions with mineral resources since this could cause damage to the well and subsequently result in ground water contamination. Furthermore, this method is only cost effective for disposal of large volumes of processed fluid (Mickley, 1993). Since our design project involves small scale production of fresh water, the brine volume for disposal would be small and thereby render the deep well injection method not cost effective and while risking aquifer contamination.

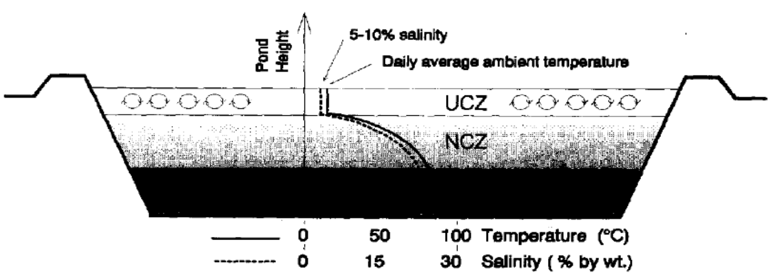
Solar Ponds

Solar ponds are salinity gradient ponds which are developed as an integrated system for membrane desalination coupled with brine disposal. This technology produces electricity using brine as a main constituent. The salinity gradient solar pond is an integrated collection and storage device of solar thermal energy. The process starts when large quantities of salt are dissolved in the hot bottom layer of the body of water, this will make this layer of water too dense to rise up to the surface and cool. Generally there are three main layers in a solar pond. The top layer is cold and has low salt content. The bottom layer is hot and very salty. Separating these two layers is the important gradient zone where salt content increases with depth and where water in the gradient cannot rise due to the above lighter water layer which contains less salt. The water below the gradient zone is heavier because of its volume of salt content which is large. Therefore, the steady gradient zone restrains convection and acts as a transparent insulator which permits sunlight to be trapped in the hot bottom layer. The hot bottom layer heat could be then withdrawn or stored for later use in electricity generation. However, to have effective electricity generation, solar ponds require:

• large volumes of brine, as well as an adequate source of 'fresher' water
• cheap, flat land, of low permeability, and high thermal and structural stability
• pond area (minimum size one hectare and maximum of ten hectares) (Ahmed et al., 2001)

Once again, since this method requires large volumes of brine disposal we cannot implement this technique for our design project since we will be dealing with a small scale desalination plant which produces low brine effluent and disposes of a relatively small land area for the installation of the brine disposal equipment and technology.

Figure 5: Salt gradient non-convective solar pond (Ahmed et al., 2001).



Evaporation Ponds

Brine disposal is normally seen as a major issue in the engineering design of any desalination facility. Evaporation ponds have been used over the centuries to remove water from saline solution. This relatively easy to construct technology requires low maintenance as well as little operator attention compared to mechanical systems since the only mechanical equipment needed is the mechanical pump to convey the wastewater to the pond. At this time method is the most wide spread brine disposal technique for inland based desalination facilities (Mickley, 1993).

Evaporation ponds are designed to process small desalination brine effluent (less than 5 million gallons per day) and generally restricted to arid climatic regions which have high evaporation rates and availability of land at low cost. Evaporation ponds are designed to concentrate the received effluent and reduce its volume through evaporation. A number of small ponds are constructed and connected by a pipeline. Each pond requires a liner of clay or synthetic membranes such as PVC or Hypalon in order to prevent any seepage and contamination of the ground water aquifers. Unlined ponds located in light soils can leak and result in the movement of salts to the groundwater. To be sufficient for the disposal of the brine solution, our design implementation will consider two adjacent small evaporation ponds connected by a pipeline located 30 cm above the bed of the pond. In addition, by concentrating the brine, evaporation basins offer the opportunity to develop systems such as aquaculture, brine shrimp, beta-carotene production (Ahmed, 2001).

4. DESIGN METHODOLOGY

4.1. DESCRIPTION OF SITE AND CONTEXT

Jordan's potential water resources are estimated to be roughly 1000 MCM or 1200 MCM if the potential for recycled wastewaters is taken into account. Of this value, 750 MCM can be sustainably sourced from renewable ground and surface water. An additional 143 MCM can be supplied from the non-renewable fossil waters referenced earlier. It has also been determined that 50 MCM of fresh water can be sourced from the desalination of brackish ground and spring water that is available around the country. Although the brackish spring water sources are scattered and are difficult to exploit on a large scale, they will be able to supply desalted water for small, remote communities by utilizing solar and or wind energy (Mohsen, 2007).

A multi-objective analysis was performed to evaluate the relative importance of different non-conventional sources of water for Jordan and its results (see figure)show that desalination is the most feasible based on economic, technical, availability, reliability, and environmental factors (Jaber et al., 2001). More specifically, the desalination of brackish water is far more economical than seawater on a small scale. Since energy consumption in the process is directly related to the operating pressures, and operating pressure is directly related to the concentration of dissolved solids in the feed water, one can conclude that desalinating brackish water (1-10 g/L TDS) as compared to seawater (35 g/L TDS) would require less energy and the product would have a lesser cost (Mohsen, 2007).

Though Jordan is surrounded by many oil-rich nations it has very few of its own fossil fuel reserves and must therefore develop alternative sources of energy for its growing needs. A multi-criteria analysis was performed in order to analyse the feasibility of using different non-conventional energy sources to power desalination processes in Jordan, finding that solar energy may be economically used to produce water for domestic usage as based on criteria of environmental sustainability (Akash et. al, 1997). Average annual solar radiation on a horizontal surface in Jordan has been found to range from 5-7 kWh/m^2/day depending on location, making it one of the richest countries in the world in terms of solar resources (Abdallah, 2005). Although water demand is highest during the dry summer months, this is also the time period with the highest rates of solar radiation and sunshine duration (see Figures 6 and 7), further solidifying the decision to utilize solar power for desalination of brackish water.

Figure 6: Mean monthly variation of the recorded global solar radiation for Jordan, 1994–2003 (Hrayshat, 2009).

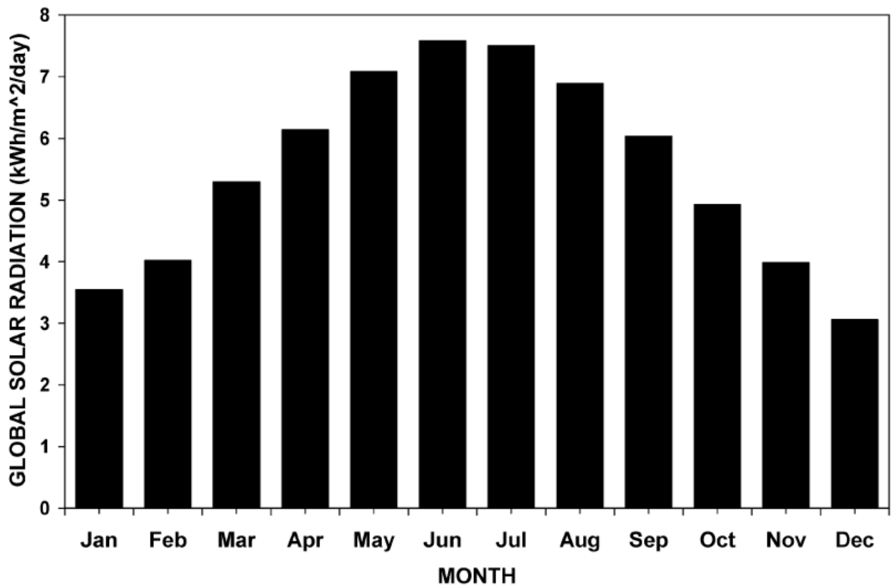
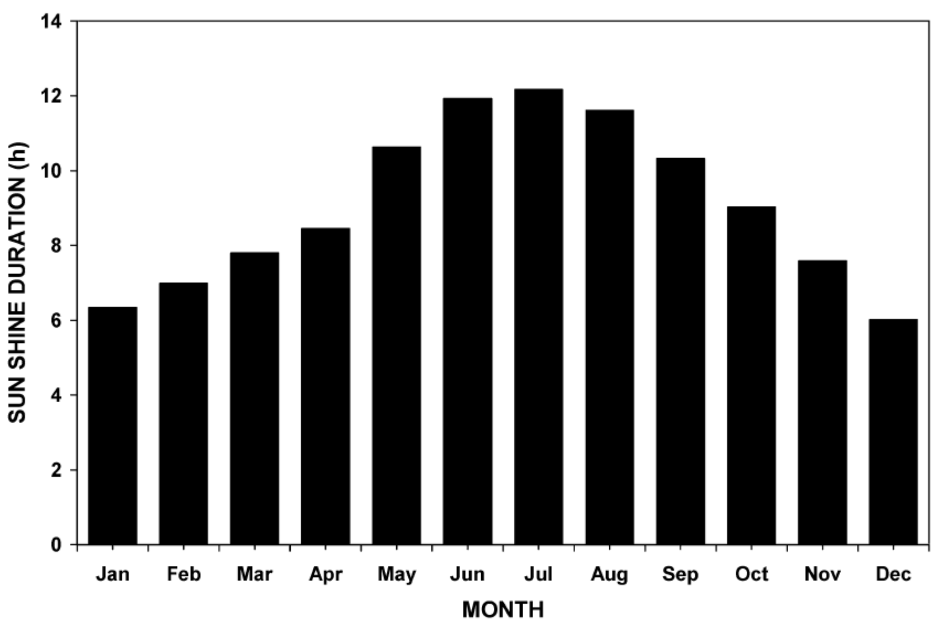


Figure 7: Mean monthly variation of the recorded sunshine duration for Jordan, 1994-2003 (Hryashat, 2009).



4.2 SELECTION OF TECHNOLOGIES

4.2.1. RENEWABLE ENERGY SYSTEM

An array of solar photovoltaic units is the chosen source of renewable power for the desalination process in this design. This technology has been on the market for a very long time and current efficiencies are higher than ever. Innovation in the solar photovoltaic industry has lead to development of special coatings which increase resistance to damage from sand storms which makes this technology ever more suitable for applications in the desert.

The potential of photovoltaic energy generation has been well studied in Jordan and precise data is available from a long-term study (1994-2003) of 24 locations around the country (Hrayshat, 2008 (2)). Due to the incredible abundance of solar resources in Jordan, utilizing this resource is the most logical and cost-effective option.

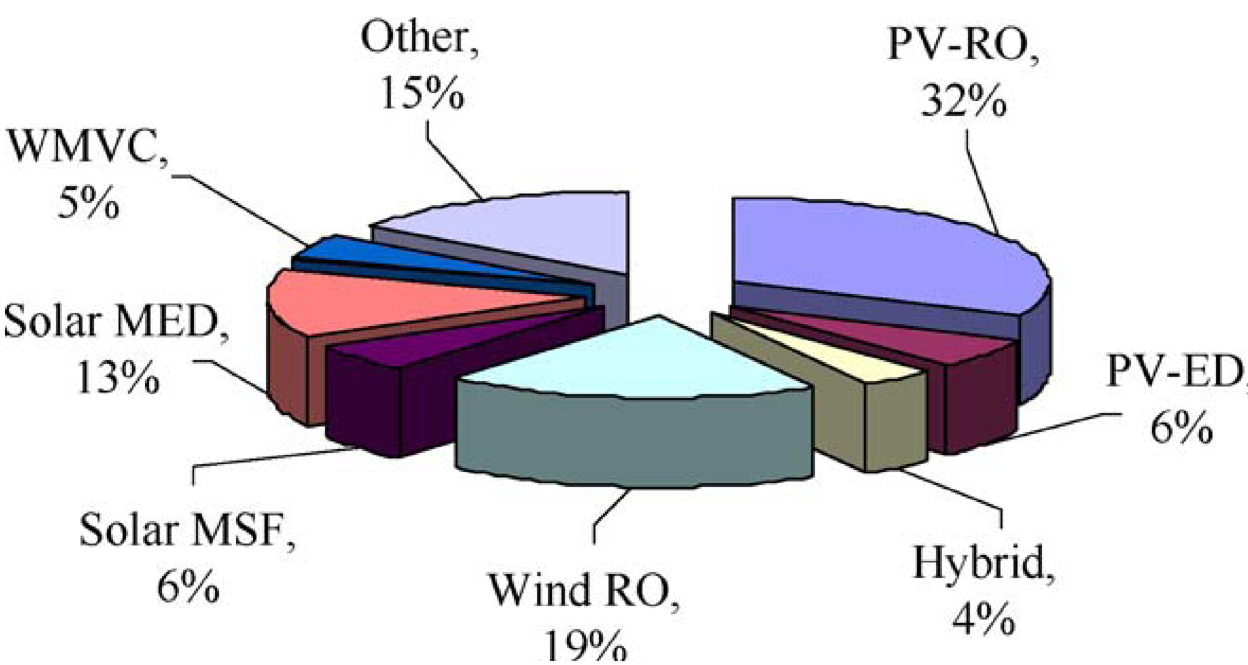
4.2.2. DESALINATION UNIT

Over the last twenty years desalination using membrane technology has been established as a flexible, low-cost solution to the production of potable water from brackish groundwater. The combination of reverse osmosis with a solar photovoltaic energy source is the most popular method for desalination worldwide (see Figure 8). Brackish water RO is typically the lowest capital investment and operating cost solution for most applications given its relatively low overall energy consumption and ease of manufacture and construction. According to factors such as total power consumption, capital cost, reliability process, and availability. Table 2 gives us an idea about which process is best for our situation.

Table 2 : Desalination Technologies Overview (Eltawil et al. 2009)

Technology	Capital Cost	Reliability	Availability	Water Specific Cost	Total Average Energy Consumption	Maintenance
	($/MGD)		%	$	(kWh/m³)	
MVC	5	Medium	96	Moderate	13.25	high
MED	4.5	Medium	96	Low	8.2	medium
RO	**4**	**High**	**96**	**Low**	**1.75**	**low**

Figure 8: Renewable energy – desalination combinations worldwide (Eltawil et al., 2009).



Brackish Water Reverse Osmosis (BWRO)

Brackish water are any water sources with TDS between 1000 and 15 000 mg/L. Brackish water cannot be consumed by us directly due to its high salinity. According to World Health Organization (WHO), water with salinity below 500 mg/L is acceptable as drinking water (Alghoul et al., 2009). With much research done on BWRO, it has been established to be the most economical and reliable process as compared to the MVC and the MED. BWRO systems which have been tested in real situations have improved recovery percentage for small scale desalination operations. When effectively operating a BWRO system, then the reduction of energy consumption is considerable and this could eventually be reduced to less than 1.75kWh/$m^{3,}$ which is lower than the total energy consumption of MVC and MSF. Furthermore, reverse osmosis requires less maintenance since there is no need to control temperature at all stages of the process such as in MED (Afonso et al., 2003). From this, we conclude that our main choice of desalination would be reverse osmosis since all the important factors are acceptable for the reverse osmosis compared to the other type of technologies.

4.2.3 PRE/POST-TREATMENT UNIT

Much research has been done to study the water quality at numerous locations in Jordan (Hryashat, 2008(1)., Jaber et. al, 2001., Mohsen, 2007.). This research will be referenced when making decisions related to the composition of the feed water such as selection of pre and/or post treatment units

When the source of the feed water that needs treatment is specified, it will be an important step for the design of a pre-treatment system and the entire reverse osmosis system, because this will determine the type and size of the pre-treatment. The limiting factor for the treatment of brackish water with a reverse osmosis system is mainly its chemical nature. This means precipitation and scaling caused by calcium carbonate or sulphates. The chemical composition of brackish waters varies a lot and is very location specific. To produce an acceptable process design, we will have to rely on a very accurate water analysis to be carried out at our specific location.

4.2.4 BRINE DISPOSAL UNIT

The evaporation pond has been chosen as the optimal method of brine disposal for a rural location in Jordan. This method of inland brine disposal requires the least capital investment and is appropriate for treating smaller scale desalination plant effluent. Away from the cities, large areas of land should be available at low cost, making this an appropriate selection. Also, the possibility of aquaculture and the revenues associated with salt production make this an enticing solution. From this we can conclude that this method could be suitable for our design report for a proper brine disposal for a small scale desalination plant since evaporation ponds remain in many cases the most cost-effective means of saline water disposal.

4.3 DESIGN APPROACH

A basic schematic of a RO desalination plant is shown in Figure 10. It is important to note that two RO units will be required, and therefore two identical inverters, two high pressure pumps, and two of each type of valve required. This is essential to the design because if one of the units is under maintenance or repair, the backup unit will continue to produce water. This design ensures a reliable production of fresh water will be ensured.

The systemic design of a renewable energy powered desalination unit follows the flowchart as seen in Figure 9. The first step is to identify the quantity of fresh water needed by the community in consideration for this project. It is necessary to communicate with the community we are intending to help with this project in order to find out what their water demands are and what the end use of the desalinated water will be. Once the community's demand is determined, the capacity of the desalination unit will be sized to match. The renewable energy system can then be designed based on the energy demand from the desalination unit and the associated pre/post-treatments as well as the pumps needed to run the process.

To appropriately size the energy system, we must first determine the loads.

Sizing the Brackish Water Pumping System

After the desired output of the desalination plant is determined, the volume of feed water necessary can be determined based on the water recovery efficiency of the selected system. Once the desired flow rate of the pump is determined, the hydraulic energy required will be:

$$E_{\mathrm{h}} = \rho g Q h,$$

where

ρ, standard water density $= 1000\,\mathrm{kg/m^3}$,
G, gravity acceleration $= 9.81a\,\mathrm{m/s^2}$,
h, total pumping head $= 8\,\mathrm{m}$,
Q, daily needed brackish water $= 20\,\mathrm{m^3/day}$.

The daily required energy from the PV generator will be:

$$E_{PV} = \frac{E_h}{\zeta_{inv}} \zeta_{mp},$$

where

ζ_{inv}, efficiency of the DC/AC inverter ;
ζ_{mp}, efficiency of the motor-pump unit

Once required energy (kWh/day) is determined, the peak power required from the PV generator is calculated as (with a safety factor of 1.25):

$$P_{PV} = \frac{(1.25 \times E_{PV})}{\text{PSH}}$$

The Peak Sunshine Hours (PSH) is calculated as:

$$\text{PSH} = \frac{E_{sd}}{G_o}$$

E_{sd}, the daily average of solar radiation intensity

G_o, the peak solar radiation intensity

Determining RO Energy Requirements

Based on data from the manufacturer of the RO unit, electrical consumption per unit water produced can be determined as a function of feed water composition. The energy required for the RO unit will be:

$$E_{PVR} = \frac{E_{RO}}{\zeta_{inv} \times \zeta_B \times \zeta_R}$$

ζ_{inv}, efficiency of the DC/AC inverter
ζ_B, efficiency of the storage batteries ;
ζ_R, efficiency of the batteries charge regulator

The peak power required by the RO unit can then be determined, taking into account a safety factor of 1.25 for each of the two units:

$$P_{PVR} = 2.5 \times \frac{E_{PVR}}{\text{PSH}}$$

The power required by the pumps and the RO unit can then be added together in order to determine the necessary generation capacity of the solar PV array.

Sizing the Energy Storage Battery Block

In order to make sure that energy continues to flow to the RO units even when the sun is not shining, the battery capacity needs to be sized as follows:

$$C_B = [(E_{PV} + E_{RO})/(DOD \times \zeta_B)] \times N_a$$

where

C_B = storage capacity of the battery block in kWh
E_{PV} = energy required for pumping of brackish water.
E_{RO} = energy consumed by the RO-system.
N_a = days of autonomy.
DOD = depth of discharge = 75% which is the maximum allowable discharge percentage of battery block full charge.

Once all of these calculations are performed, the pair of inverters and the battery charge regulator will be sized in order to safeguard the energy system and the RO unit from fluctuations in energy production in the solar PV array.

Figure 9: RES-desalination design algorithm (Eltawil et al. et. Al, 2009).

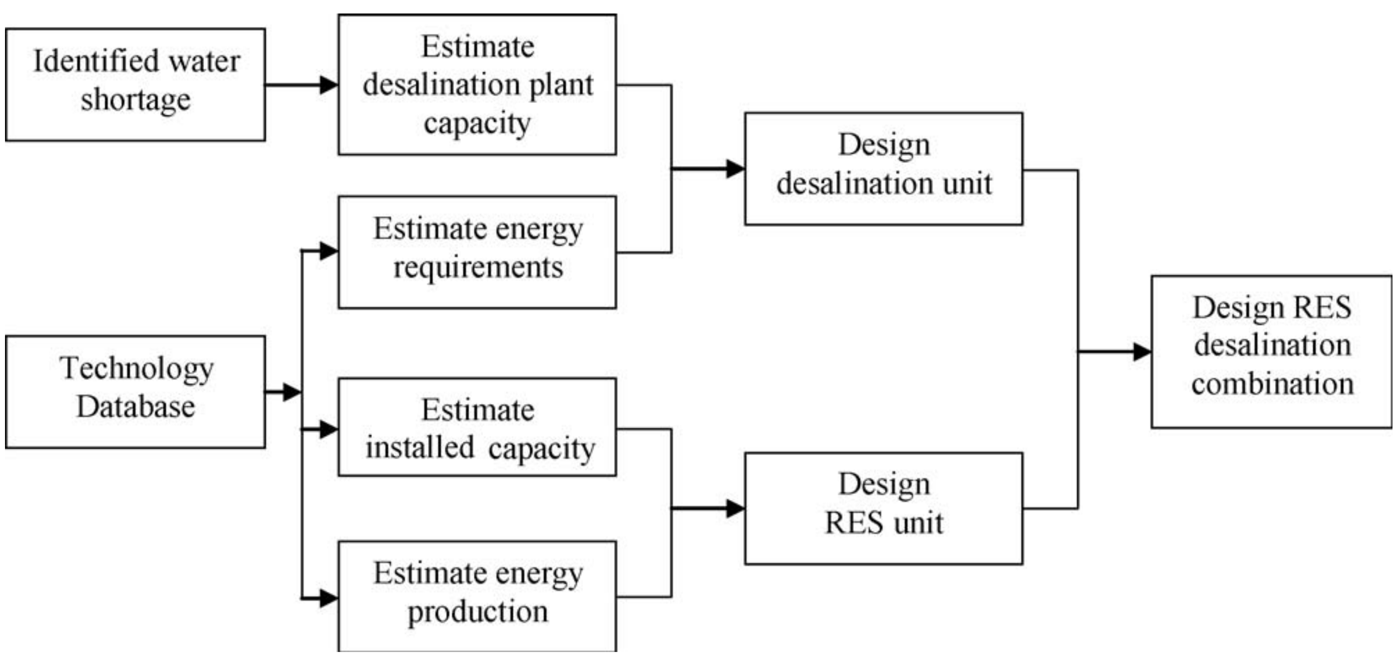
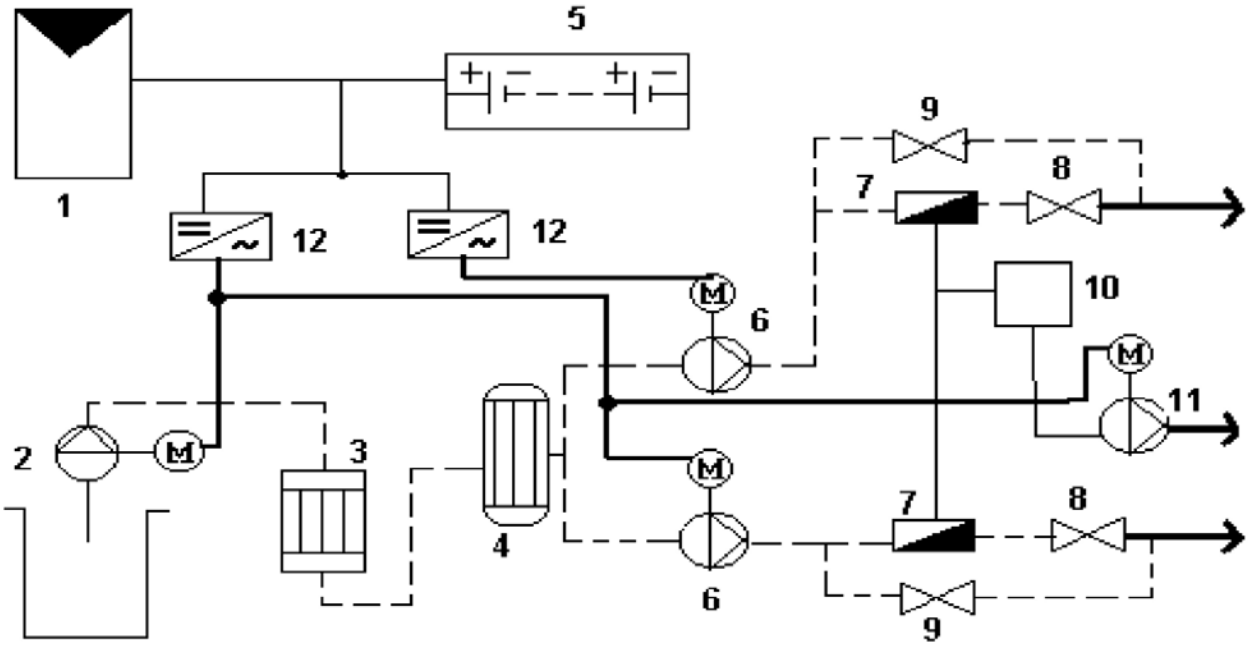


Figure 10: Block diagram of the proposed PV-powered BWRO desalination plant (Mahmoud, 2003).



1, Solar Generator; 2, Well Pump; 3, Sand Filter; 4, Cartridge Filter; 5, Battery Block; 6, High Pressure Pumps; 7, RO-Modules; 8, Regulating Valves; 9, Starting Valves; 10, Product Water Storage; 11, Product Water Pump; 12, DC/AC 3 Phase Inverter.

Design of the Evaporation Pond

The proper sizing of an evaporation pond will depend on accurate calculation of the annual evaporation rate. As we know, evaporation functions by shifting liquid water in the pond to water vapour in the atmosphere above the specific pond itself. The evaporation rate will determine the surface area required while the calculation of depth is based on water storage, and storage capacity for the salt. Salinity of the water influences the rate of evaporation; they are indirectly proportional to each other. As the salinity increases, evaporation rates decreases. In order to maximize the rate of evaporation, the recommended pond ranging depth is optimal from 25 to 45 cm. This optimal depth must be respected since very shallow evaporation ponds can be easily subjected to drying and cracking of the liners. As we know the rate of evaporation varies from location to location, therefore accurate evaporation data are required for designing an efficient evaporation pond. It is necessary to ensure that the average annual evaporation depth exceeds the depth of water that would have to be stored in the pond (Ahmed et al, 2001).

According to the design and maintenance of evaporation ponds proposed by Ahmed et al , the pond open surface area (A) and minimum pond depth (d) can be estimated from:

$$\mathbf{A= V*f_1/ (0.7*E_{ave})}$$

$$\mathbf{D_{min}= 0.2+E_{ave}*f_2}$$

Where A is the open surface area of the pond (m^2), V is the volume of rejected water (m^3/d), E_{ave} is the average evaporation rate (m/d) which can be determined using the pan evaporation rate method. F_1 is an empirical safety factor to allow for lowers than average evaporation rates, D_{min} is the minimum depth (m) and $f_2$is a factor that incorporates the length of the winter season. The value of 0.7 in the area equation represents the evaporation ratio for multiplying calculated solar evaporation rate to incorporate the effect of salinity. The value of 0.2m in the depth equation is the freeboard for rainfall intensity, duration as well as wind speed action likely to be produced in the pond. In other words the freeboard is defined as the depth above the normal reject water surface, so that during low evaporation periods, will not cause rejection of water to spill out of the pond. The design of the evaporation pond considers carefully the surface area, depth and freeboard of such installation, since these are the factors that are determined by the rates of concentrate discharge relative to surface evaporation rates. Therefore, it is clear that the area needed is directly proportional to volume of reject water and inversely proportional to the evaporation rate (Ahmed et al, 2001).

Liners

Liners are the most important aspect of an evaporation pond, as they should be mechanically strong to withstand stress during salt cleaning and also be impermeable. The evaporation pond liners need to be installed in accordance with manufacturer's instructions. Sealing of the liners is critical, especially along joints and adjacent sections of the liner, in order to eliminate pond leakage and subsequent aquifer contamination. Therefore, double lining of polyethylene or other impervious polymeric sheets or linings is strongly recommended with leakage sensing probes installed between layers of pond lining. It is of utmost importance to have careful environmental monitoring of the potential pond leakage, since a variety of toxic chemicals can be produced in desalination plant operation that includes chemicals used in membrane cleaning and pre-treatment that could cause major potential risks for the contamination of the ground water aquifer (Ahmed et al., 2001).

Construction Location

The basin of the pond can be a natural basin from a depression in the earth surface such as a saline lake, or dry natural depressions. Also, a modified natural depression or constructed basin which could be excavated on location may be considered as an option. The design of this project basin is considered to be a small manageable pond. The small scale pond is advantageous especially in windy conditions where wind could not damage the top surface of the embankment or levee and therefore the pond would lessen the maintenance costs. In order to dissipate wind damage on the pond, one needs to remove the top soil where the bank is to be located and then the length of the pond should be placed at right angles to the predominant direction of wind. Again, suitable site location is very important. Basins located in non-heavy soils will seep out and as consequence will induce the movement of salts to the groundwater (Ahmed et al., 2001).

Banks of the basin should be 1 m in height and 2.4 minimum wide at the crest to allow for the movement of light vehicles in and out of the pond. In addition, in order to lessen bank erosion, the inside slope is recommended to be 1:5 slope in order to absorb most of the wave energy, The outside bank can be constructed at a 1:2 slope. Furthermore, using a sheepsfoot roller, the banks are compacted during the construction operation. In order to have an even spread of water and an increase in evaporation, laser levelling of the bed is required. As an additional precaution in order to control lateral seepage, a small diameter interception well could be employed along the perimeter of the pool area, from which the effluent would be pumped back in the basin (Ahmed et al., 2001).

5. EXPECTED RESULTS

The results that will be produced at the end of the design phase are as follows:

1) System design of a brackish water desalination facility for a remote community in Jordan. Components will include a renewable energy system, a desalination unit, pre and/or post treatment units if necessary, a brine disposal system, as well as all of the associated pumps and storage tanks. Manufacturers and materials will be chosen and each component will be sized according to the needs of the facility.

2) A cost evaluation for the purchase, installation, operation, and maintenance of the system will be performed in order to determine the unit cost of product water. The economic analysis will include a comparison of projected water production costs for this specific system with known costs for desalination plants of similar and larger scale powered by both conventional and renewable energies. Savings from elimination of transportation costs and potential increases of income from larger irrigation capacities and improved personal health of community members will also be taken into account.

6. TIME FRAME

January 2010	•Continue literature review (20 hours) •Develop a preliminary design (30 hours)
February 2010	•Identify materials (15 hours) •Identify manufacturers (15 hours)
March 2010	•Finalize system design (30 hours) •Generate design plans (20 hours) •Perform economic analysis (20 hours)
April 2010	•Complete final report (20 hours) •Prepare and deliver final presentation (10 hours)

It is expected that the design phase will require approximately 180 hours of total work by the two engineers involved with this project in order to produce the deliverables outlined in the "Expected Results" and "Time Frame" sections of this report. As with any project unexpected tasks and challenges may arise throughout the design process and increase the amount of hours currently allocated.

7. COST EVALUATION

Although the engineering team performing the system design will not be compensated monetarily for their work on this project, a comparable job would be performed by junior engineers each earning a salary of $25/hr. At this rate, the cost of a completed design would amount to a total of $4,500. It is probable that a consulting engineer would need to be hired to review the work of the junior engineers for technical accuracy. We estimate the consulting engineer would take approximately 5 hours to perform an evaluation and suggest modifications. At a rate of $100/hr, the cost of hiring a consultant would be $500, thereby bringing the total cost of system design to $5000.

8. CONCLUSION

The Kingdom of Jordan is a country in which the desalination of brackish water has been determined to have the greatest potential to alleviate the current condition of water scarcity (Jaber et al., 2001). Because the problem is so severe in Jordan, we have elected to complete the system design for a small-scale desalination project for a rural community in this country.

Although the price of desalinated water increases with smaller scale projects, the need for decentralized water treatment is reinforced by the extremely high losses (over 50%) associated with the current water distribution network and by the increasingly high cost of water transport to remote locations. It has been determined that for a small community with a population of 200 people consuming 0.40 m^3/day per capita, a locally sited solar desalination unit would provide water at a lower cost than if it had to be transported from greater than 16km away (Akash et. al, 1997). It is our goal to design a desalination system which will be a cost-effective solution to water shortages for a rural community.

Although this design is not currently being completed for a real client, the need for this type of development in Jordan is very apparent. We have engaged in communication with Dr. Mark Zeitoun of East Anglia University in the UK after meeting him during his visit to Macdonald Campus in the fall of 2009. He has informed us that one of his colleagues has expressed interest to him in selecting a Jordanian village for a project very similar to ours and we are excited to make contact with this individual to obtain more site-specific information necessary for completion of the design. We are also hopeful that our design work could contribute to the implementation of such a project in the real-world.

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