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Solar Desalination to Solve the Problem at the On-Site Level: A Case Study at Wadi Al-Maleh Village

M.Sc. Thesis

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Dedication

*To our prophet Mohammad
Blessings and Peace be upon him*

To my father

To my mother

To my wife

To all of them,

I dedicate this work

Acknowledgments

First of all, praise be to Allah for helping me in making this thesis possible.

I would like to express my sincere thanks to my advisor Professors for his guidance, inspiration, support and encouragement in every stage of my study, but also for providing me with an excellent atmosphere and giving me trust and freedom to carry out the research. His vision, optimistic attitude, enthusiasm and continual pursuing for scientific and industrial challenges have provided me with lifetime benefits.

My parents, wife, brothers, sisters, and my big family, thank you for being a great source of support and encouragement. I am grateful to all of you for your love, support, and patience. All my friends and fellow graduate students, thank you.

I would like to thank the Palestinian Water Authority (PWA) and the Middle East Desalination Research Center (MEDRC) for the financial and moral support that they gave me to complete my study.

إننا الموقع أدناه مقدم الرسالة التي تحمل عنوان

Solar Desalination to Solve the Problem at the On-Site Level: A Case Study at Wadi Al- Maleh Village“

أقر بأن ما اشتملت عليه هذه الرسالة إنما هو نتاج جهدي الخاص، باستثناء ما تمت الإشارة إليه حيثما ورد، وأن هذه الرسالة كاملة، أو أي جزء منها لم يُقدم من قبل لنيل أي درجة أو لقب علمي أو بحثي لدى أي مؤسسة تعليمية أو بحثية أخرى.

Declaration

The work provided in this thesis, unless otherwise referenced, is the researcher's own work, and has not been submitted elsewhere for any other degree or qualification.

Student's Name:

اسم الطالب:

Signature:

التوقيع:

Date:

التاريخ:

List of Symbols

a	Length of PV array in front of the second array installed to the north (m)
C_{Ah}	Ampere-hour capacity of battery (Ah)
C_b	The concentration of salts in the solution except the membrane surface
C_{fm}	Mean salt concentration in feed stream
C_p	Salinity of the permeate
CPF	Concentration polarization factor
C_s	concentration of salts at the membrane surface
C_{wh}	Watt hour capacity of battery (Wh)
d	membrane thickness (mm)
D	number of days per year that the system is operated
DOD	Permissible depth of discharge (%)
EC	Electrical Conductivity ($\mu\text{S}/\text{cm}$)
E_{dl}	Daily load energy (Wh/day)
E_{PV}	Photovoltaic energy (Wh)
E_{sd}	The average daily solar radiation intensity for a month
G_o	the peak solar radiation intensity = $1000\text{W}/\text{m}^2$
I_{mpp}	Current at maximum power point (A)
I_{sc}	Short circuit current (A)
K_s	membrane permeability coefficient for salt
L_{at}	Latitude (degree)
NOCT	Nominal Operating Cell Temperature ($^{\circ}\text{C}$)
P	Cost of one m ³ from potable water from water delivery trucks (\$)
P_{LT}	Total load power (W)
P_M	Module power (Wp)
P_{osm}	osmotic pressure (bar)
P_{PV}	Photovoltaic power (Wp)
PSH	The average Peak Sun Hours around the year (h)
PSH_m	The average Peak Sun Hours around month
Q_f	Feed water flow rate (m^3/h)
Q_{favg}	Average feed flow rate (m^3/h)
Q_p	Product water flow rate (m^3/h)
Q_s	Flow rate of salt (m^3/h)
Q_w	Flow rate of water (m^3/h)
R	Recovery rate (%)
R_i	Permeate recovery rate of membrane element
S	membrane area (m^2)

SP	Salt passage (%)
SR	Salt rejection (%)
T	Temperature (°C)
T_a	Ambient temperature (°C)
T_c	Cell temperature (°C)
t_d	Time of operation system in a day (h)
TDS	Total dissolved solids (mg/L)
V_B	Nominal voltage of the battery bank (V)
V_{mmp}	Voltage at maximum power point (V)
V_{OC}	Open circuit voltage (V)
X	Distance between the two PV arrays facing south (m)
X	Amount of CO ₂ produced by burned of 1 liter diesel (kg/L)
Z	saving in diesel per day (l/day)
η_{in}	Efficiency of inverter (%)
η_{cc}	Efficiency of battery charge controller (%)
η_B	is the ampere hour efficiency of the battery cell (%)
B	Tilt angle of the PV array on a horizontal level amounting to (degree)
ΔC	salt concentration differential across the membrane
Σ(mi)	Sum of molal concentration of all constituents in a solution (mol/L)

Solar Desalination to Solve the Problem at the On-Site Level: A Case Study at Wadi Al-Maleh Village“

Abstract

Brackish Water Reverse Osmosis (BWRO) desalination technology powered by solar PV system is considered as one of the most promising technology in producing potable water from both brackish and sea water. Even such small systems located in remote areas can break the dependence on conventional desalination by fossil fuels, reduce the costs of potable water, and improve the environmental sustainability.

This thesis discusses the energy required, the techno-economic issues, and environmental analysis of the first BWRO desalination system operated by solar electric power (PV) in West Bank- Palestine. This system is built in village—Jordan valley to demonstrate the applicability of solar energy in water desalination and to provide the inhabitants with the desalinated drink water.

Energy analysis shows that 1 m³ of produced potable water needs 2.3 kWh of electrical energy, which corresponds to 450 W_p PV modules.

Economic analysis shows that the cost of 1 m³ of potable water produced by this system is 3.17\$ when using battery bank and 2.33\$ without using battery. This result is very reasonable compared with 5.07\$/m³ as cost of potable water delivered by trucks. The annual savings by using such system amount to 17740\$.

VIII

Investigations on varying the recovery has shown that higher recovery results in higher power requirement of the high pressure pump, and thereby higher energy consumption of the system, it increases also the TDS of permeate which results in higher probability of membrane scaling.

Environmental analysis shows that using such a small system preserves the environment of production 4195 kg of CO₂ per year.

Introduction

Introduction

Water is the most basic resource for human existence. It is essential element for human life itself and for personal health and hygiene. The Palestinian territories suffer from one of the worst water shortages of all the countries in the Middle East, and have one of the most underdeveloped water sectors. Palestinians water supplies are currently insufficient to meet demand, and are increasingly degraded, due to high population growth, increasing living standards and rapid industrial growth, in addition to extremely exploited of all Palestinian water basins and water sources by Israeli occupation that instituted restrictions and prohibitions in water sector.

On the other hand and for the same previous reasons the demand of energy increased in the Palestinian Territories in recent years. The energy situation in Palestine is highly different compared to other countries in the Middle East due to non-availability of natural resource, financial crunch and unstable political condition. Palestine is heavily dependent on Israel for meeting its energy requirements. Almost all petroleum products are imported through Israeli companies. Israel controls energy imports into Palestine and thus prevents open trade in electricity and petroleum products between Palestine and other countries.

Palestine has a large number of rural villages lacking for potable water and electricity networks. For securing potable water many communities depend on water delivery trucks, which cost so much and cause air pollution.

With regard to electricity networks, connecting some of these villages with electric grids from the nearest cities seems to be impossible, due to their

remoteness, few population and low electric energy demands.

Some of these villages have large amount of brackish water (BW), which can be desalinated by solar energy to provide the inhabitants with enough drinking water. The reason behind choosing solar energy is that Palestine has one of the highest solar energy potential in the world. It enjoys over 2800 sunshine hours every year, with an annual average daily solar radiation intensity amounting to $5.4 \text{ kWh/m}^2\text{-day}$, as illustrated in the chapter four.

These facts are encouraging to use solar energy for electricity generation and desalination of BW, especially in non-electrified rural villages.

Thesis Objectives

1. Provide the inhabitants of Wadi Al- Maleh village with potable drink water from the available BW by using solar energy.
2. Study in brief the different desalination technologies.
3. Study and design (BW) reverse osmosis (RO) desalination systems powered by solar electric energy.

Thesis Structure

The works done in this thesis are summarized in eight chapters as follows:

Chapter 1: Water Status around the World and Water Status in Palestine

This chapter explains the water status around the world represented in water situation around the world and an overview of the global water problems, also it explains water status in Palestine represented in water resources and water consumption.

Chapter 2: Desalination Technologies

This chapter illustrates desalination technologies, classification of these technologies, advantages and disadvantages of each technology, and makes comparisons between all this technologies.

Chapter 3: RO Desalination Method.

This chapter discusses Osmosis and RO method in terms of definition, classification of filtration mechanisms. It gives also a historical background about RO System, RO process terminology and equations related to RO technology. It discusses pretreatment of feed water in RO system and RO membrane modules, and explains the design of RO system in general.

Chapter 4: Solar Energy in Palestine

This chapter describes the potential of solar energy in Palestine and ambient temperatures in Palestine.

Chapter 5: Photovoltaic Cell Technology

This chapter illustrates PV cell technology in terms of operating principles, cell types, (I-V) curve for PV cell and (STC). Also this chapter studies the effect of solar radiation and cell temperature on PV performance, and presents the types of PV system.

Chapter 6: Case Study; Design of Wadi Al- Maleh BW Desalination System By Using RO Membrane Powered by PV System

This chapter discusses the Wadi Al- Maleh BW desalination system, and presents the village location, physical characteristics, Population, and water quality. Also it explains the design of this system using Reverse Osmosis System Analysis (ROSA) program.

Chapter 7: Economic Analysis and Environmental Impact of Using BWRO Desalination System Powered by PV System

This chapter presents the economic analysis of Using BWRO desalination system powered by PV system with and without battery bank. Also it explains the environmental impacts of using Solar PV systems and the effect of brine related to Wadi Al- Maleh project.

Chapter 8: Conclusions and Recommendations

This chapter describes the main conclusions about BWRO desalination system powered by PV system and thereby the related recommendations.

Chapter One
Water Status around the World and Water Status in
Palestine

1.1 Water Status around the World

1.1.1 Overview of water situation around the world

About 75% of the earth's surface is covered by water. The distribution of water on the Earth, based on human economic needs for freshwater, is represented. The left-side bar shows where the water on Earth exists, about 97% of all water is in the oceans. The middle bar shows the distribution of freshwater that is only 3% of all Earth's water. However, the physical state of water, including the freshwater, is not always liquid.

Nearly 69% of freshwater is locked up in glaciers, icecaps and permanent snow covers of both poles, mountainous regions and in Greenland. Land based glaciers affect stream flow quantity and provides water resources to the lowland regions, while 30% of freshwater comes from groundwater. Only 0.3% of the freshwater on Earth is contained in river systems, lakes and reservoirs, which are the water we are most familiar with and the most accessible water source to satisfy human needs in our daily lives.

Even though three quarters of the earth's surface is covered by water, not all of that water is available for human uses. Figure (1.1) shows that more than 99% of all water (oceans, ice, most saline water and atmospheric water) is not available for our uses. Even of the remaining fraction of 1%, much of that is stored in the ground. Surface water sources (such as rivers and lakes) only form 88% of the total water. [1]

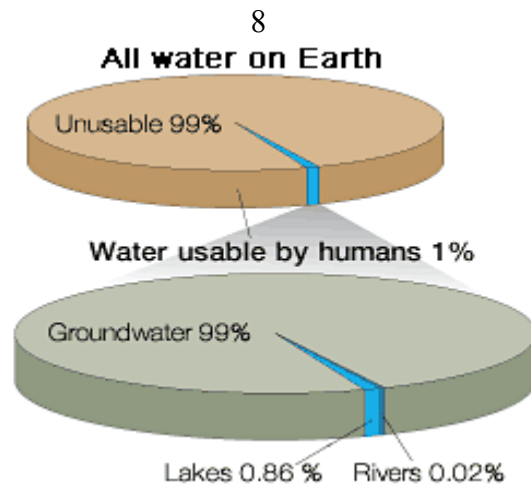


Figure (1.1): Earth's water available for human uses.

Here we can see that water is generally classified into surface water and groundwater. Surface water is water found in a river, lake or other surface impoundment. Surface water is exposed to many different contaminants, such as animal wastes, pesticides, insecticides, industrial wastes, and many organic materials. Groundwater is the part of precipitation that infiltrates down through the soil until it reaches rock material that is saturated with water. Water in the ground is stored in the spaces between rock particles, and slowly moves underground, generally at a downward angle, and may eventually seep into streams, lakes and oceans. Groundwater is not always accessible, and sometimes is difficult to locate or to measure and describe. Compared to surface water, groundwater is not as easily contaminated, but once it is contaminated, the full remediation and recovery is not easily achieved. [1]

1.1.2 Overview of the global water problems

Water is essential for human life, development and environment, but it is a finite and little resource which has quantitative limitations and qualitative sensitivity. As People Action International (PAI, 1997) states, water is the source of life and development on earth. Life is tied to water, air and food,

while food is tied to water. Water is a regional resource, but water shortage is becoming a global issue due to increasing population, economic growth and climate change and pollution of fresh water resources (rivers, lakes and underground water) by industrial wastes.

Development of new sources of water beside its efficient use together with conservation measures, and works on desalination system, study it should be an important component of any country's national water plan.

According to a PAI (1999) estimate, there were 31 countries with a total population of 458 million which faced water stress in 1995. More seriously over 2.8 billion people in 48 countries will face water stress by 2025, based on United Nations medium population projections, figure (1.2) shows the number people in water scarce countries. Of these 48 countries, 40 are in the Middle East and North Africa. Predicts that population increase alone will push all of the Middle East into water scarcity over the next two decades. [2]

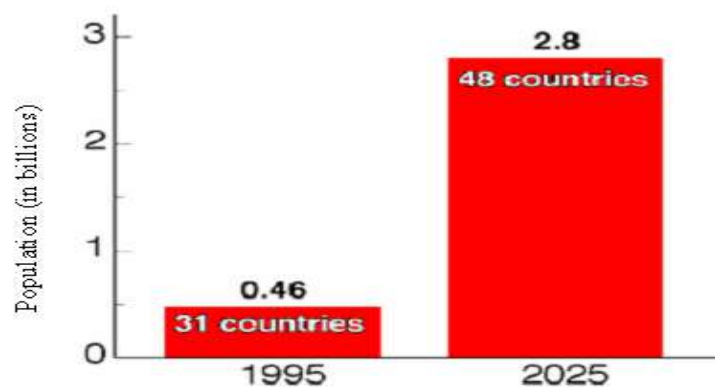


Figure (1.2): Population in water scarce and water stressed countries, 1995–2025 [2].

From the above figures it may be concluded that the world is already facing severe water-related problems, these may be identified as follows:

- 20% of the world's population or more than 1 billion people lack access to safe drinking water.
- 50% of the world's population or more than 3 billion people lack access to sanitation.
- About 80% of all illnesses and more than one third of all deaths in developing countries are related to water. It is estimated that worldwide, around 7 million die yearly from diseases linked to water. Every eight seconds a child dies from water related illness that is about 4 million a year.
- Half of the world's rivers and lakes are seriously polluted. Pollution of the waterways and surrounding river basins has created millions of environmental refugees.
- Major rivers from the Yellow river in China to the Colorado in North America are drying up and barely reaching the sea.
- Nearly half a billion people in 31 countries face water shortage problems, a number that is expected to rise to nearly two thirds of the world population by 2025. The worst areas comprise the entire Mediterranean region, including parts of southern Europe, North Africa and Middle East, Northwest and south India, Mongolia, northern China, most of Sub-Sahara Africa and major regions in North and South America, especially the western United States. They will face severe water shortages in the coming years. Europe as a whole also

faces severe problems, because half of its lakes have already atrophied. [2]

1.2 Water Status in Palestine

1.2.1 Water resources in Palestine

Palestinian water sources, including those shared with the Israeli side, are estimated by 2,989 million m^3 per year. Of this, groundwater constitutes approximately 1,454 million m^3 . Surface water includes water generated by the natural flow of the Jordan River (around 1,320 million m^3) and water flowing from torrents (around 215 million m^3). In general, almost 2,570 million m^3 is used for various purposes. Out of this quantity, Palestinians use only 271 million m^3 , or 11%, whereas Israel consumes the rest (89%). In spite of their inalienable right thereto, Palestinians are further prohibited from accessing and using the Jordan River water [3].

The principal water resources available to Palestinians include groundwater, springs, and harvested rainwater. There is little surface water and thus groundwater is the principal source of water in the West Bank [4].

Surface water (in winter time) drains either westwards to the Mediterranean or eastwards to the Jordan River and Dead Sea, the lower Jordan River flows southwards at the eastern edge of the West Bank from Lake Tabaria to the Dead Sea [4].

The West Bank lies over the Mountain aquifer. The Mountain aquifer is divided into the eastern aquifer, the northeastern aquifer, and the western aquifer as depicted in figure (1.3). The eastern aquifer flows east towards the Jordan River. The western aquifer flows westerly towards the Mediterrane-

an Sea [4].

None of these aquifers is completely encompassed within the West Bank political boundaries; however, the recharge areas of these basins fall within the West Bank boundaries [4].

The aquifer systems rely on recharge from rainfall to a great deal of extent. In the last five years, rainfall dropped significantly by 20 to 30 %. As a result, a drastic drop in the water table elevation was noticed in many wells across the West Bank. It was noticed that around 5 to 10 m drop in the water table elevation in these wells was due to recent drought as a result, the average recharge volume from rainfall had also dropped by 10 to 20 % [4].

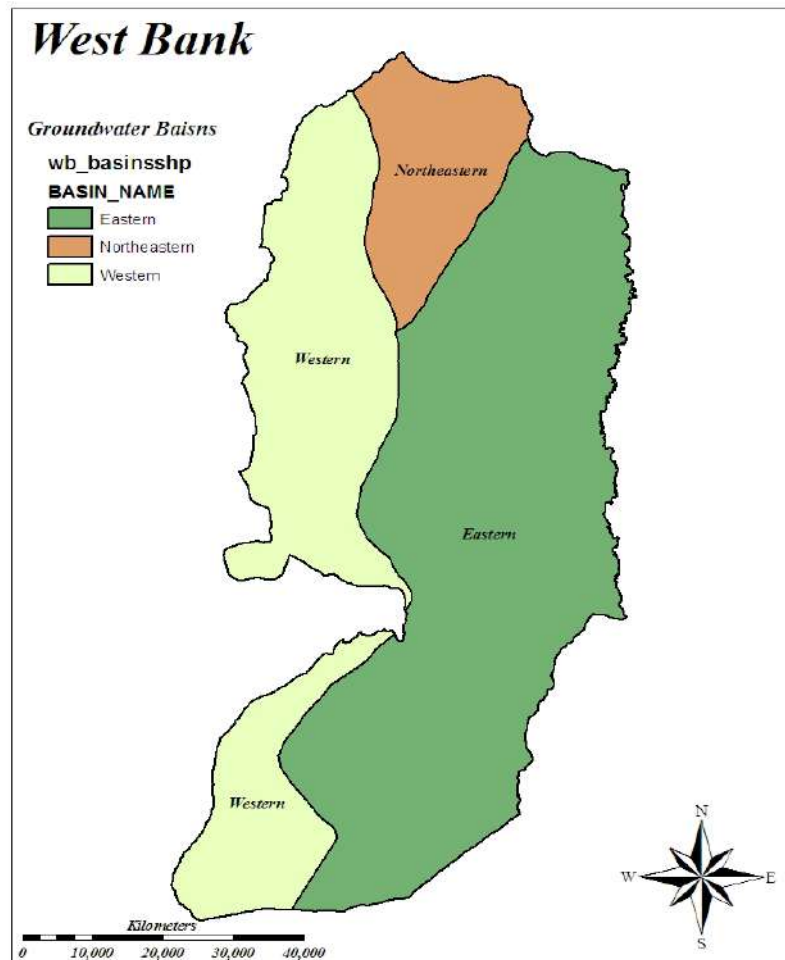


Figure (1.3): Northeastern, Western, and Eastern Aquifer Basins of the West Bank.

On the other hand, it was also noticed that in the hydrologic year 1991/1992 where rainfall exceeded the average by far, the water table elevations went up, this rise in the water table at different wells is the outcome of the increase in recharge as a result to the increase in rainfall [4].

The quantity of cross boundary fluxes between the groundwater aquifer basins and the inter-aquifer flow within the basins are not well understood, making it difficult to accurately quantify the total groundwater storage and yield in each aquifer system (PWA, 2001b). This uncertainty is reflected by the wide ranges given for each basin, as shown in Table (1.1).

Table (1.1): Reported annual recharge rates of the groundwater basins in the West Bank (PWA, 2001b).

Aquifer basin	Annual recharge rate (million m ³)
Eastern	100 – 172
North eastern	130 – 200
Western	335 – 380
Total	565 – 752

Regionally, the Jordan River is about 260 km long and drains a total area of 18,300 km². The river is composed of four tributaries: Baniyas, Hasbani, Dan, and Yarmouk. Baniyas, Hasbani, and Dan meet in the north of Palestine to form the Upper Jordan River that flows into Lake Tabaria [4].

However, Yarmouk River flows in a southwesterly direction into the Lower Jordan River forming the border between Jordan and Syria and Jordan and Palestine. Yarmouk River has a higher flow during winter which dilutes the increasing salinity of the Jordan River [4].

A large amount of BW is available in West bank. In eastern aquifer and Jordan Valley area the most ground water is salty and the salts content var-

ies in the range (1800 - 7500 mg/L) while the upper limit allowed for drink water is 1000 mg/L [5] see table (1.2).

The total flow of 1578 million m³/year from the Jordan River is unavailable because it involves BW, and the possible desalination of BW existing in both the West Bank and Gaza Strip are currently estimated at 90 million m³/year (as indicated in the Oslo Accords) [6].

The following table shows the classification of water according to its salinity (the dissolved salt content such as (sodium chloride, magnesium ... etc), of a body of water, and based on US standards.

Table (1.2): Classification of water according to salinity.

Water Type	Salinity TDS (mg/L)	Electrical Conductivity (μS/cm)
Fresh water	0-1000	0-1600
Brackish water, mildly	1000-5000	1600-8000
Brackish water, moderately	5000-15000	8000-24000
Brackish water, heavily	15000-35000	24000-56000
Sea water	30000-50000 mg/L	48000-80000
Brine	Greater than 50000	Greater than 80000
Dead sea	330000	528000

Last column in table (1.2) calculated by using the following equation;

$$\text{EC } (\mu\text{S/cm}) \times 0.625 = \text{TDS (mg/L)}$$

But this equation gives an approximate result; because there is no exact relationship between EC (μ S/cm) and TDS (mg/L), it has been discovered experimentally that for particular types of water there is an approximate relationship. The ratio of TDS to EC of various salt solutions ranges from 0.55 to 0.7, in water with a higher proportion of sodium chloride the ratio of TDS to EC is equal 0.64 [7].

1.2.2 Water consumption in Palestine

The average water supply to the Palestinian communities of the Occupied Territories is about 63 liter per capita per day (L/c/day) in the West Bank and (140 L/c/day) in the Gaza Strip. However, water supply significantly varies throughout the Territories. In (7 %) of the Palestinian communities, is less than or equal to (30 L/c/day), in (36 %) of them it is between (30- 50 L/c/day), in (41 %) of them it is between (50 – 100 L/c/day), and finally, only in (16%) of them is (100 L/c/day), which is the minimum amount recommended by the WHO [8].

1.2.3 Categories of drinking water standards

There are two categories of drinking water standards (US EPA, 2006; WHO, 2006):

a. Primary standards

These standards are legally-enforceable standards that apply to public water systems. Primary standards protect drinking water quality by limiting the levels of specific contaminants that can adversely affect public health and are known or anticipated to occur in water. They take the form of Maximum Contaminant Levels (MCLs) (US EPA, 2006). MCL is the highest level of a contaminant that is allowed in drinking water. MCLs are set as close to the Maximum Contaminant Level Goals (MCLGs) as feasible, using the best available treatment technology and taking cost into consideration. MCLs are enforceable standards. MCLG is the level of a contaminant in drinking water below which there is no known or expected risk to health. MCLGs allow for a margin of safety and are non-enforceable public health

goals (US EPA, 2006) [9].

Table (1.2): A variety of primary standards of the drinking water quality with necessary information [9].

Class	Contaminant	MCLG (mg/L)	MCL (mg/L)	Potential Health Effects from Ingestion of Water	Sources of Contaminant in Drinking Water
1	Cryptosporidium	0.0	0.0	Gastrointestinal illness	Human and fecal animal waste
2	Trihalomethanes (THMs)	None	0.1	Liver, kidney, nervous system problems; increased risk of cancer	By product of drinking water disinfection
3	Chloramines	4	4	Eye/nose irritation; anemia	Additive to control microbes
4	Nitrate	50	50	Shortness of breath for infants and blue-baby syndrome	Runoff from fertilizer use; leaching from septic tanks
5	PCBs	0.0	0.0005	Skin changes; immune deficiencies; increased risk of cancer	Runoff from landfills; discharge of waste chemicals
6	Uranium	0.0	30 µg/L	Increased risk of cancer, kidney toxicity	Erosion of natural deposits

Table (1.2) lists a number of these contaminants with their MCLs, MCLGs, potential health impacts, and sources of contaminants according to the following classes:

- a. Microorganisms: like Cryptosporidium, Giardia, and Total Coliforms.
- b. Disinfection by products: like Trihalomethanes and Haloacetic acids.
- c. Disinfectants: like Chlorine and Chloramines.
- d. Inorganic Chemicals: like Arsenic, Lead, Nitrate, and Nitrite.
- e. Organic Chemicals: like Benzene and Polychlorinated Biphenyls

(PCBs).

f. Radio nuclides: like Radium 226 and Uranium.[9]

b. Secondary Standards

The table below shows a variety of Secondary Standards of the drinking water quality [9].

Table (1.3): A variety of Secondary Standards of the drinking water quality.

Contaminant	Secondary Standard
Aluminum	0.05 to 0.2 mg/L
Chloride	250 mg/L
Color	15 (color units)
Copper	1.0 mg/L
Corrosivity	Non corrosive
Fluoride	2.0 mg/L
Foaming Agents	0.5 mg/L
Iron	0.3 mg/L
Manganese	0.05 mg/L
Odor	3 threshold odor number
pH	6.5-8.5
Silver	0.10 mg/L
Sulfate	250 mg/L
TDS	500 mg/L
Zinc	5 mg/L

1.2.4 Water Quality in Wadi Al- Maleh Village

1.2.4.1 Water quality analysis

Wadi Al- Maleh village has only three wells with BW. The BW from one well is pumped to a cement storage tank, located at 45m higher than the level of the village. The inhabitants of the village use the water from the tank for different purposes but not for drinking. Two samples from well, and two samples from tank are taken for analysis at different periods (one in June 2011, and another in September 2012), these analysis were con-

ducted in Water and Environmental Studies Institute (WESI) laboratories, in Bir Zeit University, there is no noticeable difference between the results of the analysis between the two different periods. Table (1.4) shows water quality analysis of Wadi Al- Maleh well and storage tank which was conducted in September 2012.

Table (1.4): Water quality analysis of Wadi Al- Maleh

Quality Parameter	Unit	Wadi Al- Maleh
TDS	mg/L	2681
TSS	mg/L	9
pH		7.78
Chloride	mg/L	1200
Sodium	mg/L	473
Sulfate	mg/L	166
Magnesium	mg/L	158
Calcium	mg/L	220
Potassium	mg/L	15.5
Iron	mg/L	0
Bicarbonate	mg/L	305
Bromide	mg/L	12.4
Silica	mg/L	26.6
Boron	mg/L	0.53
Nitrate	mg/L	37.6
Hardness	mg/L as CaCO ₃	1199
SAR*		4.04
Turbidity	NTU	1.2
Sediments after week		None

* Sodium adsorption ratio (SAR): is a measure of the suitability of water for use in agricultural irrigation, as determined by the concentrations of solids dissolved in the water. It is also a measure of the solidity of soil, as determined from analysis of water extracted from the soil [10].

The formula for calculating sodium adsorption ratio is:

$$\text{SAR} = [\text{Na}^+] / \{([\text{Ca}^{2+}] + [\text{Mg}^{2+}]) / 2\}^{1/2}$$

Where sodium, calcium, and magnesium are in milliequivalents/liter (meq/L), the unit of SAR is (meq/L)^{1/2} [10].

Although SAR is only one factor in determining the suitability of water for irrigation, in general, the higher the sodium adsorption ratio, the less suitable the water is for irrigation. Irrigation using water with high sodium adsorption ratio may require soil amendments to prevent long-term damage to the soil [10].

If irrigation water with a high SAR is applied to a soil for years, the sodium in the water can displace the calcium and magnesium in the soil. This will cause a decrease in the ability of the soil to form stable aggregates and a loss of soil structure and tilth. This will also lead to a decrease in infiltration and permeability of the soil to water leading to problems with crop production [10].

1.2.4.2 Comparison between water quality of Wadi Al- Maleh water tank and WHO drinking water standards

The analysis in table (1.4) indicates that the water salinity is too high for drinking which limits it only for irrigation purposes. The water is very hard, has TSS and SiO₂ content and turbidity which makes it very appropriate for desalination by RO membranes. Table (1.5) shows the parameters that cause high salinity and hardness in table (1.4) which are underlined, and the parameters at the appropriate level, all comparison with WHO standards.

Table (1.5): Comparison between water qualities for Wadi Al- Maleh water tank and WHO drinking water standards.

Parameter	Concentration (mg/L)	WHO(mg/L)
<u>Potassium</u>	<u>13.1</u>	<u>12</u>
<u>Sodium</u>	<u>483</u>	<u>200</u>
<u>Magnesium</u>	<u>146</u>	<u><125</u>
<u>Calcium</u>	<u>200</u>	<u>75</u>
<u>Chloride</u>	<u>1200</u>	<u>250</u>
<u>Boron</u>	<u>0.46</u>	<u>0.3</u>
Sulfate	157	500
Nitrate	36	50
<u>Hardness as CaCO₃</u>	<u>1098</u>	<u>500</u>
TDS	2636	500

Chapter Two

Desalination Technologies

Introduction

The techniques for desalination classified into three categories according to the process principle used:

- Process based on a physical change in state of the water i.e. distillation or freezing.
- Process using membranes i.e. RO or ED.
- Process acting on chemical bonds i.e. ion exchange.

Of the above processes, that based on chemical bonds such as ion exchange are mainly used to produce extremely high quality water for industrial purposes and are not suited to treating BW [11], there for this process is not discussed in this thesis.

The other widely known two processes are discussed in this thesis is:

a. Process based on a physical change in state of the water (evaporation - distillation):

- Multi Stage Flash (MSF) Evaporation/ Distillation.
- Multi Effect Evaporation/ Distillation.
- Vapor Compression Distillation.

b. Process using membranes filtration:

- Microfiltration.
- Ultrafiltration.
- Nanofiltration.
- Reverse Osmosis.
- Electrodialysis.

2.1 Process Based on a Physical Change in State of the Water (Evaporation/Distillation)

2.1.1 Multi stage flash evaporation/distillation (MSF)

In MSF evaporation the saline water (sea or brackish) is heated and evaporated, the pure water is then obtained by condensing the vapor. When the water is heated in a vessel both the temperature and pressure increase, the heated water passes to another chamber at a lower pressure which causes vapor to be formed; the vapor is led off and condensed to pure water using the cold sea water which feeds the first heating stage. The concentrated brine is then passed to a second chamber at a still lower pressure and more water evaporates and the vapor is condensed as before. The process is repeated through a series of vessels or chambers until atmospheric pressure is reached. Typically, MSF plant can contain from 4 to about 40 stages. MSF is considered to be the most reliable, and is probably the most widely used of the three principal distillation processes. This principle is illustrated in figure (2.1) which shows just three stages, in commercial plant many more stages are used [12].

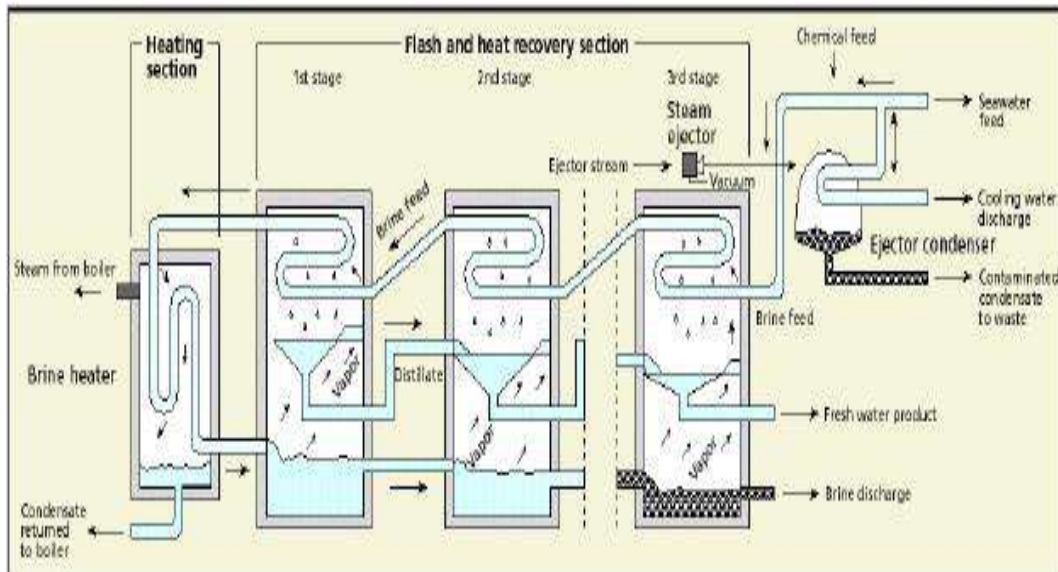


Figure (2.1): Simplified diagram of the MSF process [11].

➤ Advantages and disadvantages of this method

- The advantages of using MSF for desalination water are:

- MSF plants can be constructed to handle large capacities.
- The salinity of the feed water does not have much impact on the process or costs.
- It produces very high quality product water (less than 10 mg/L TDS).
- There is only a minimal requirement for pre-treatment of the feed water.
- Easy operational and maintenance procedures compared with other processes.
- There is a long history of commercial use and reliability.
- It can be combined with other processes, i.e. using the heat energy from an electricity generation plant.

- The disadvantages of using MSF for desalination are:

- It's expensive to build and operate and require a high level of tech-

nical knowledge.

- b. Highly energy intensive due to the requirement to boil the feed water.
- c. The recovery ratio is low; therefore more feed water is required to produce the same amount of product water.
- d. The plant cannot be operated below 70-80% of the design capacity.
- e. Blending (post treatment) is often required when there is less than 50 mg/L TDS in the product water. [11]

2.1.2 Multiple-effect evaporation/distillation (MED)

MED is also known as long-tube vertical distillation, in this method the steam is used to heat up the seawater in the first stage and the resulting vapor is used in subsequent stages to evaporate the water, and the seawater brine is used to cool and condense the vapor in each successive stage so that the temperature gradually falls across each stage of the process. As in MSF evaporation, many stages are used in commercial plants. This principle is illustrated in the figure (2.2) [12].

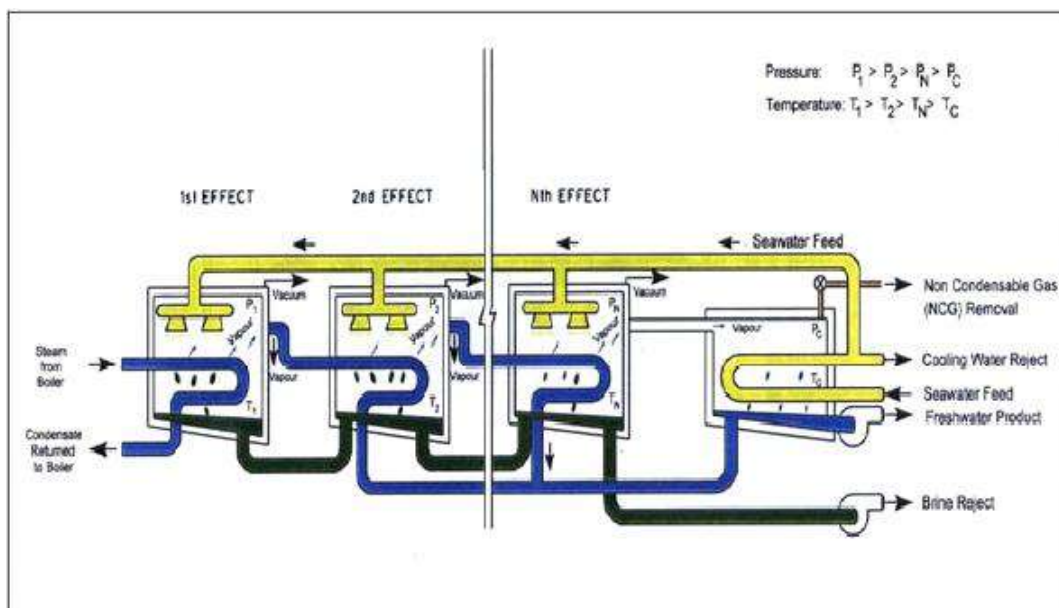


Figure (2.2): Simplified diagram of the MED process [11].

➤ Advantages and disadvantages of this method

- The advantages of using MED for desalination are:
 - a. The pre-treatment requirements of the feed water are minimal.
 - b. Product water is of a high quality.
 - c. MED plants are very reliable.
 - d. The plant can be combined with other processes, i.e. using the heat energy from a power plant.
 - e. The requirements for operating staff are minimal.
- The disadvantages of using MED for desalination are:
 - a. It's expensive to build and operate and energy consumption is particularly high.
 - b. The plant can be susceptible to corrosion. This can usually be controlled by the choice of material.
 - c. The product water is at high temperature and can require cooling before it can be used as potable water.
 - d. The recovery ratio is low, but not as low as MSF. [11]

2.1.3 Vapor compression distillation (VCD)

Steam is generated from the seawater using a source of heat and the vapor is then compressed using a compressor. As a result of this compression the temperature and pressure of the steam is increased i.e. the work done in compressing the vapor is changed into heat, (you notice this effect when pumping up a bicycle tire and the pump warms up). The incoming seawater is used to cool the compressed steam which then condenses into distilled (fresh) water and at the same time the seawater is heated further producing

more steam. The principle is illustrated in figure (2.3).

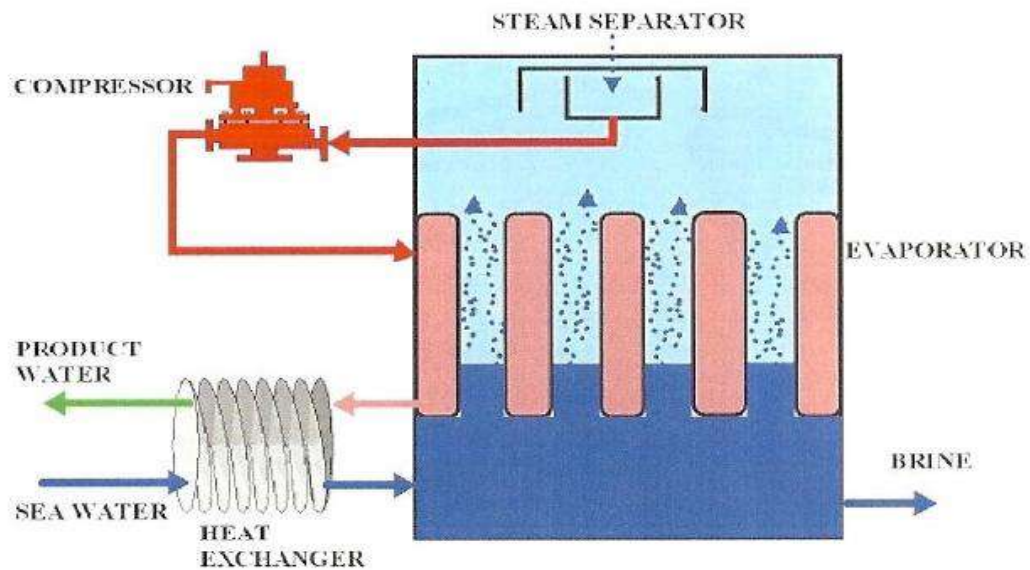


Figure (2.3): Simplified diagram of the VCD process [11].

VCD is usually used where the requirement for desalinated fresh water is relatively small such as in small communities, ships or in holiday resorts [12].

➤ Advantages and disadvantages of this method

• The advantages of using VCD for desalination are:

- a. The plants are very compact and can be designed to be portable.
- b. Minimal pretreatment is required.
- c. The capital cost of the plant is reasonable and operation is simple and reliable.
- d. The recovery ratio is good.
- e. The product water is a high quality.
- f. The energy requirements are relatively low, but not as low as RO.

- The disadvantages of using VCD for desalination are:
 - a. Starting up the plant is difficult. An auxiliary heater is normally required to get the temperature of the feed water up to a point where some vapor is formed. After this the compressor can take over.
 - b. It requires large, expensive steam compressors, which are not readily available. [11]

2.2 Process Using Membranes Filtration

What is membranes filtration?

Filtration is a process of removing particulate matter from water by forcing the water through a porous media (membranes). This porous media can be natural, in the case of sand, gravel and clay, or it can be a membrane wall made of various materials.

2.2.1 Microfiltration (MF)

MF removes particles in the range of approximately 0.1 to 1 micron (1.0×10^{-6}). In general, suspended particles and large colloids are rejected while macromolecules and dissolved solids pass through the MF membrane. Applications include removal of bacteria, flocculated materials. Trans Membrane pressures are typically 0.7 bar [13].

2.2.2 Ultrafiltration (UF)

UF provides macro-molecular separation for particles in the 20 to 1,000 Angstrom range (1 angstrom = 1.0×10^{-10} meters). All dissolved salts and smaller molecules pass through the membrane. Items rejected by the membrane include colloids, proteins, microbiological contaminants, and large organic molecules. Trans Membrane pressures are typically 1 to 7 bar [13].

2.2.3 Nanofiltration (NF)

NF refers to a specialty membrane process which rejects particles in the approximate size range of 1 nanometer (10 Angstroms), hence NF operates in the realm between UF and RO. Organic molecules with molecular weights greater than 200-400 are rejected. Also, dissolved salts are rejected in the range of 20-98%. Salts which have monovalent anions (e.g. sodium chloride or calcium chloride) have rejections of 20-80%, whereas salts with divalent anions (e.g. magnesium sulfate) have higher rejections of 90-98%. Typical applications include removal of color and total organic carbon (TOC) from surface water, removal of hardness or radium from well water, overall reduction of total dissolved solids (TDS), and the separation of organic from inorganic matter in specialty food and wastewater applications. Trans Membrane pressures are typically 3.5 to 16 bar [13].

2.2.4 Reverse osmosis (RO)

The following is a brief explanation for RO desalination system and it will explain in details in chapter three.

RO is the finest level of filtration available. The RO membrane acts as a barrier to all dissolved salts and inorganic molecules, as well as organic molecules with a molecular weight greater than approximately 100. Water molecules, on the other hand, pass freely through the membrane creating a purified product stream. Rejection of dissolved salts is typically 95% to greater than 99%.

The applications for RO are numerous and varied, and include desalination of seawater or BW for drinking purposes, wastewater recovery, food and

beverage processing, biomedical separations, purification of home drinking water and industrial process water.

Also, RO is often used in the production of ultrapure water for use in the semiconductor industry, power industry (boiler feed water), and medical and laboratory applications. Trans Membrane pressures for RO typically range from 5 bar for BW to greater than 84 bar for seawater. [13]

➤ Advantages and disadvantages of this method

- The advantages of using the RO system for desalination are:
 - a. They are quick and cheap to build and simple to operate.
 - b. It can handle a large range of flow rates, from a few liters per day to 750,000 L/day for BW and 400,000 L/day for seawater. The capacity of the system can be increased at a later date if required by adding on extra modules.
 - c. It has a high space production capacity ratio, ranging from 25,000 to 60,000 L/day/m².
 - d. Energy consumption is low.
 - e. It can remove other contaminants in the water as well as the salt.
 - f. The use of chemicals for cleaning purposes is low.
 - g. The startup and shutdown of the plant does not take long time.
- The disadvantages of using the RO system for desalination are:
 - a. RO membranes are expensive and have a life expectancy of 2-5 years.
 - b. If the plant uses seawater there can be interruptions to the service during stormy weather. This can cause resuspension of particles,

which increases the amount of suspended solids in the water.

- c. There is a requirement for a high quality standard of materials and equipment for the operation of the plant.
- d. It is necessary to maintain an extensive spare parts inventory.
- e. There is a possibility of bacterial contamination. This would be retained in the brine stream, but bacterial growth on the membrane itself can cause the introduction of tastes and odors into the product water.
- f. Most failures in RO systems are caused by the feed water not being pre-treated satisfactorily. Pre-treatment of the feed water is required in order to remove particulates so that the membranes last longer. Careful pre-treatment of feed water is necessary, especially if feed water quality changes.
- g. The plant operates at high pressures and sometimes there are problems with mechanical failure of equipment due to the high pressures used. [11]

2.2.5 Electrodialysis (ED)

The salts in seawater are composed of positive ions (called cations) and negative ions (called anions). For example, common salt (which is sodium chloride, NaCl) dissolves in water to produce positively charged sodium ions and negatively charged chloride ions. ($\text{NaCl} = \text{Na}^+ + \text{Cl}^-$)

ED uses a stack of ion-exchange membranes which are selective to positive and negative ions. Under the influence of a direct electrical current (DC) the positive sodium ions pass through a cation membrane and the negative

chloride ions pass through an anion membrane as shown in figure (2.4). The incoming saline water is thus converted into two streams, one of concentrated brine and one of desalinated (fresh) water. Industrial ED plants consist of stacks of hundreds of membranes. . Fouling of the ion exchange membranes can occur and this can be partly overcome by reversing the direction of the DC current; this process is known as ED reversal (EDR). [12]

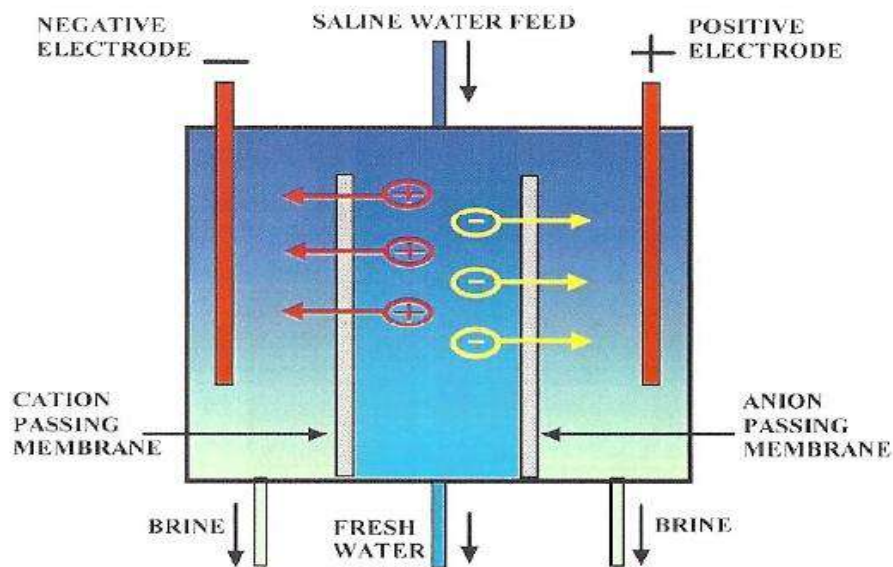


Figure (2.4): Simplified diagram of the ED process.

➤ **Advantages and disadvantages of this method:**

- The advantages of using ED for desalination are:
 - a. They can produce a high recovery ratio (85-94% for one stage).
 - b. Can treat feed water with a higher level of suspended solids.
 - c. Pre-treatment has a low chemical usage and does not need to be as precise.
 - d. The energy usage is proportional to the salts removed, instead of the volume of water being treated.
 - e. The membranes for EDR have a life expectancy of 7-10 years, which

is longer than for RO.

- f. EDR membranes are not susceptible to bacterial attack or silica scaling.
- g. Scaling can be controlled whilst the process is on-line, the membranes can also be manually cleaned.
- h. Can be operated at low to moderate pressure.
- The disadvantages of using ED for desalination are:
 - a. Periodic cleaning of the membranes with chemicals is required.
 - b. Leaks sometimes occur in the membrane stacks.
 - c. Bacteria and non-ionic substances and residual turbidity are not affected by the system and can therefore remain in the product water and require further treatment before certain water quality standards are met. [11]

2.3 Classification and Comparison between Membrane Filtration Processes.

The classification and comparison between membrane filtration processes is based on many characteristics like applied pressure, minimum particle size removed, application type particle removed and average removal efficiency (%) of each, as shown in table (2.1).

Table (2.1): Characteristics of membrane processes [14].

Membrane Process	Applied Pressure (bar)	Minimum Particle Size Removed	Application (type, average removal efficiency %)
Microfiltration	0.276-4.83	0.1-3 μm	<ul style="list-style-type: none"> - Particle/turbidity removal (>99%) - Bacteria/protozoa removal (>99.99 %)
Ultrafiltration	0.276-4.83	0.01-0.1 μm	<ul style="list-style-type: none"> - Particle/turbidity removal (>99 %) - Bacteria/protozoa removal (>99.999 %) - TOC removal (<20%) - Virus removal/(partial credit only)
Nanofiltration	4.83-9.65	0.008-0.01 μm	<ul style="list-style-type: none"> - Turbidity removal (>99%) - Color removal (>98%) - TOC removal (DBP control) (>95%) - Hardness removal (softening) (>90%) - Sulfate removal (>97%) - Virus removal (>95%)
Hyperfiltration (RO)	9.65-48	0.0001 μm	<ul style="list-style-type: none"> - Salinity removal (desalination) (>99%) - Color and DOC removal (>97%) - Radionuclide removal (not including radon) (>97%) - Nitrate removal (85 to 95%) - Pesticide/SOC removal (0 to 100%) - Virus removal (>95%) - As, Cd, Cr, Pb, F removal (40 to >98%)

2.4 Comparison between All Previous Methods

2.4.1 Use each method in the world

Figure (2.5) shows the percentage of use each method in the world, RO method is the most method use around the world.

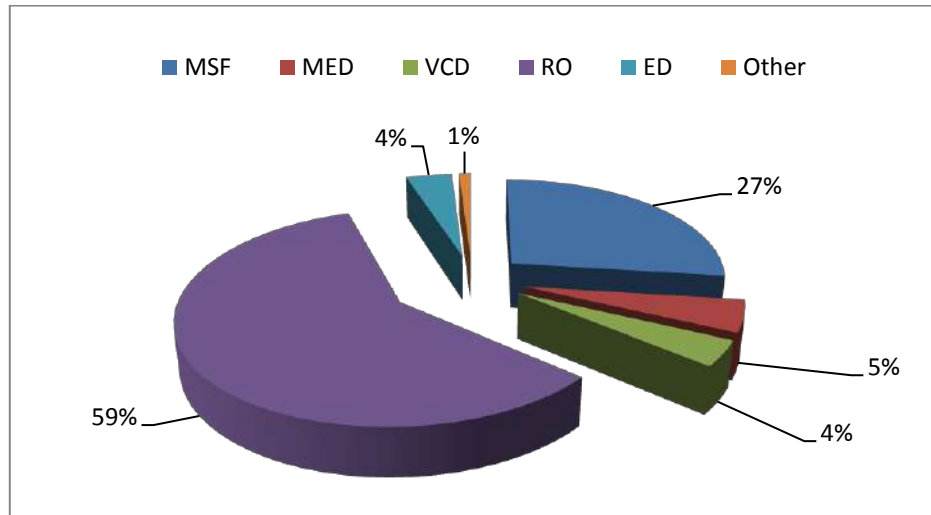


Figure (2.5): Percentage of use of different world desalinated water methods [12].

2.4.2 Total cost of each method

Table (2.2) shows total costs per m^3 permeate water produced from different desalination methods, each cost derived to many costs like energy cost, labor cost. (\$/Euro exchange rate was approximately 1:1 in 2002)

Table (2.2): Total costs of different desalination method [15].

Process	Investment In plant capacity USD/ m^3		Energy USD/ m^3		Consumable USD/ m^3		Labor USD/ m^3		Operating and Maintenance USD/ m^3		Total Running Cost USD/ m^3	
	low	high	low	high	low	high	low	high	low	high	low	high
MSF	100 0	200 0	0.6	1.8	0.03	0.09	0.0 3	0.2	0.7	2.21	1.3 6	4.3
MED	900	180 0	0.3 8	1.1 2	0.02	0.15	0.0 3	0.2	0.4 7	1.59	0.9	3.0 6
VC	900	250 0	0.5 6	2.4	0.02	0.15	0.0 3	0.2	0.6 5	2.91	1.2 6	5.6 6
SWRO	800	160 0	0.3 2	1.2 8	0.09	0.25	0.0 3	0.2	0.4 8	1.83	0.9 2	3.5 6
BWRO	200	500	0.04	0.4	0.05	0.13	0.03	0.2	0.124	0.77	0.24	1.5
ED	266	328	0.06	0.4	0.05	0.13	0.03	0.2	0.156	0.749	0.3	1.48

Energy column in table (2.2) shows that BWRO is the lowest method consume energy than any other desalination methods, therefore it's suitable to use with PV solar energy, especially in small pilot project, and the last column shows that BWRO is cheapest than any other desalination methods, thus it is the most method used around the world.

Chapter Three
Reverse Osmosis
Desalination Method

3.1 Osmosis and Reverse Osmosis Definition and Classification of Filtration Mechanisms

3.1.1 Osmosis and reverse osmosis definition

Osmosis is a natural phenomenon in which a solvent (usually water) passes through a semipermeable barrier from the side with lower solute concentration to the higher solute concentration side. As shown in figure (3.1a), water flow continues until chemical potential equilibrium of the solvent is established. At equilibrium, the pressure difference between the two sides of the membrane is equal to the osmotic pressure of the solution. To reverse the flow of water (solvent), a pressure difference greater than the osmotic pressure difference is applied (see figure 3.1 b); as a result, separation of water from the solution occurs as pure water flows from the high concentration side to the low concentration side. This phenomenon is termed RO or hyperfiltration [16].

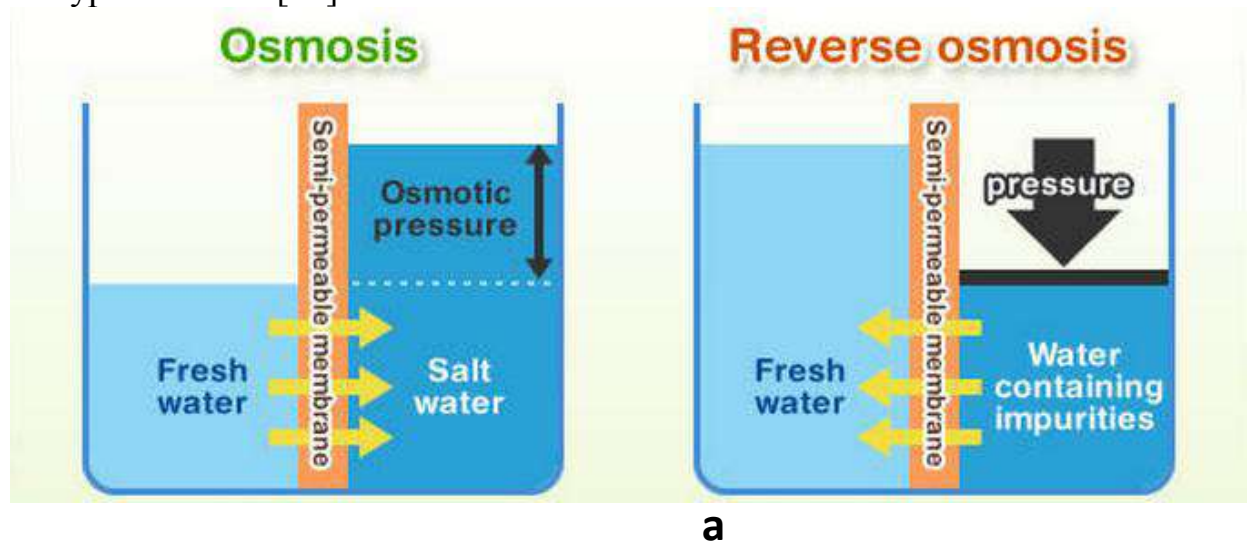


Figure (3.1): Simplified diagram of Osmosis and reverse osmosis phenomenon.

The simplified RO system is shown in figure (3.2), it's include pre-treatment of water, HP pump and RO membrane.

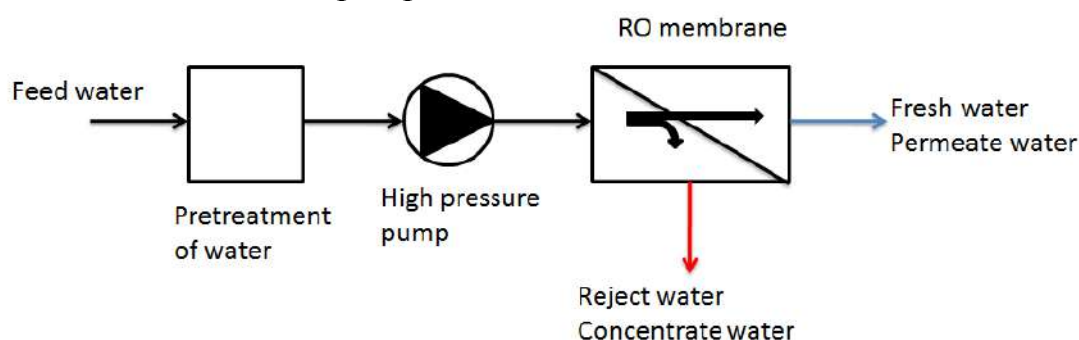


Figure (3.2): Simplified RO system.

3.1.2 Classification of filtration mechanisms

3.1.2.1 Cross-flow filtration and dead-end filtration

Filtration mechanisms can be divided by cross-flow filtration and dead-end filtration depends on the flow direction on membrane surface as shown in figure (3.3)

a. Cross-flow filtration

In cross-flow filtration the feed water flow is parallel to the membrane, a part of the feed water is used for permeate production, and another part will leave the membrane as concentrate, therefore cross-flow membranes have an inlet stream and two outlet streams. The inlet is known as the feed water and the outlets are permeate and concentrate (reject water or brine). Consequentially, cross-flow filtration has a high energy cost, and the entire feed water flow needs to be kept under pressure.

The water speed of the feed water flow parallel to the membrane is relatively high, the purpose of this flow is the control of the thickness of the cake,

consequentially to the flow speed of the water, flowing forces are high, which enables the suspended solids to be carried away in the water flow.

Cross-flow mechanism can achieve stable fluxes. Still, the cleaning of cross-flow installations needs to be applied from time to time. Cleaning is performed by means of backward flushing or chemical cleaning. An example of cross-flow filtration is RO membrane. [17]

b. Dead-end filtration

In dead-end filtration all the water that enters the membrane surface is pressed through the membrane. Some solids and components will stay behind on the membrane while water flows through; this depends on the pore size of the membrane. Consequentially, the water will experience a greater resistance to passing through the membrane. When feed water pressure is continual, this will result in a decreasing flux. After a certain amount of time the flux has decreased to such an extent, that the membrane will need cleaning.

The energy loss in dead-end filtration is less than a cross-flow filtration. This is because all energy enters the water that actually passed the membrane.

The pressure that is needed to press water through a membrane is called Trans Membrane Pressure (TMP), and it is defined as the pressure gradient of the membrane, or the average feed pressure minus the permeate pressure. The feed pressure is often measured at the initial point of a membrane module. However, this pressure does not equal the average feed pressure, because the flow through a membrane will cause hydraulic pressure losses.

During cleaning of a membrane, components are removed hydraulically, chemically or physically. When the cleaning process is performed, a module is temporarily out of order. As a result, dead-end mechanism is a discontinuous process.

The length of time that a module performs filtration is called filtration time and the length of time that a module is cleaned is called cleaning time. In practice one always tries to make filtration time last as long as possible, and apply the lowest possible cleaning time. When a membrane is cleaned with permeate, it does not have a continuous production of water, this results in a lower production. [17]

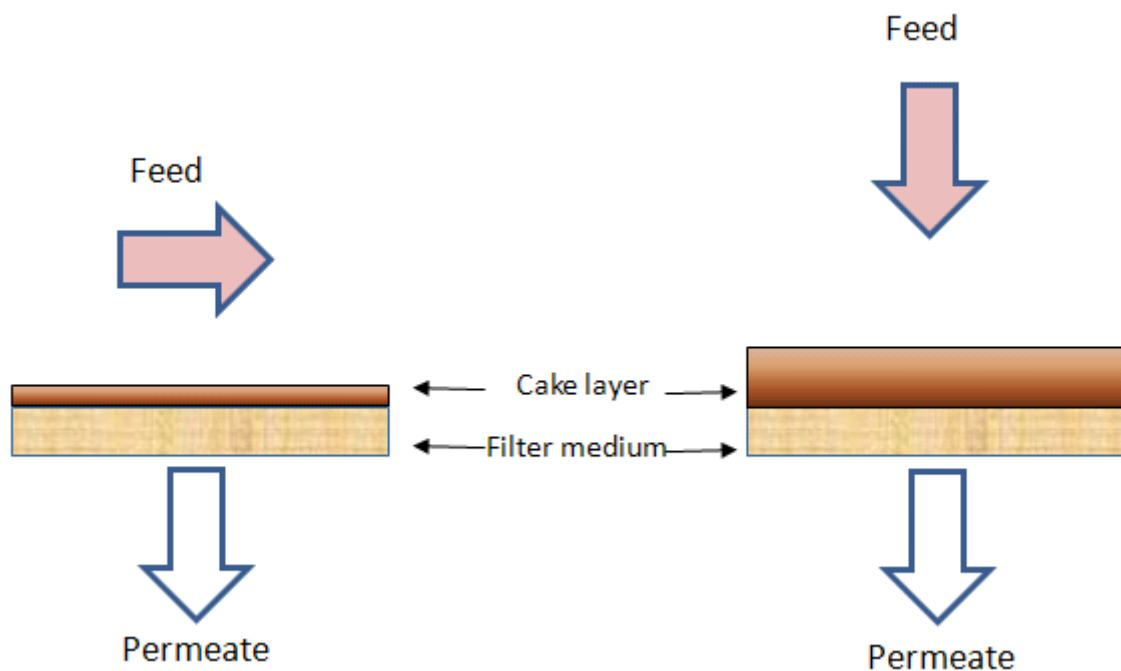


Figure (3.3): Cross-flow versus dead-end mechanisms in membrane filtration.

3.1.2.2 Surface filtration and depth filtration.

Filtration can be also divided by two depending on where the particle rejection occurs as shown in figure (3.4)

a. Surface filtration

In surface filtration, particles are supposedly rejected on the filter surface and generally do not intrude into the filter medium. RO membrane filtration from this category [17].

b. Depth filtration

In depth filtration, particles can enter filter medium and captured by the medium through collision. Since the particle removal relies on the random collision and there is no absolute barrier, some particles can pass the filter. Cartridge filter, multi-media filter, from this category [17].

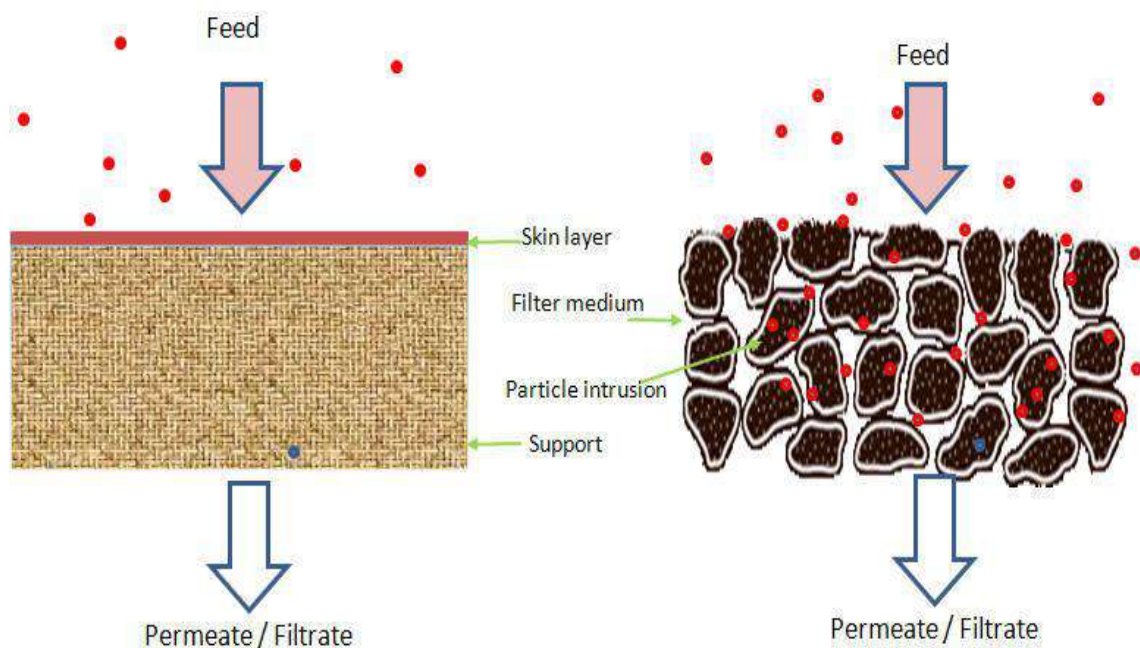


Figure (3.4): Surface filtration and depth filtration.

3.2 Historical Background of RO System

3.2.1 Examples of importance of the membranes in the life

Membranes are an essential part of being alive; several examples are simple to cite:

- The skin in all mammals is a very efficient and highly selective type of membrane controlling release of sweat to cool off the bodies

through evaporation of tinny water droplets during hot weather. Skin selectivity as apparent, when it's cut the fine blood cells and vessels that run underneath the skin are broken and releases its blood content. A healthy and intact skin does not release blood.

- The lungs are also a good example of effective membranes, where fine cells within the lungs allow passage of oxygen from the inhaled air and release CO₂ into the same stream. The lungs as a membrane prevent permeation of the nitrogen in the inhaled air, irrespective of its high content.
- The kidney membranes regulate the water, salt ions, proteins, and other nutrient within the body. The kidneys are extremely efficient that a healthy body can survive with a quarter of both kidneys.[18]
- On a much smaller scale, membrane walls in single cells within mammals, bacteria, and other microorganisms maintains the cell contents intact and regulate the input/output rates of nutrients or products.

Since the early days of civilization mankind have adopted simple forms of membranes. In early agriculture communities, household sieves were invented and developed to separate fin grain ground from coarse grain particles and shells.

Similarly, cheesecloth was made from cotton fibers and used to manufacture cheese. Both forms of separation are based on differences in particle size.

However, developments in membrane technology have focused on adop-

tion of other separation mechanisms, such differences in solution and diffusion rates of various species across the membrane material. [18]

3.2.2 Historical development for artificial membranes

Use of artificial membranes is rather new. Major landmarks in use of artificial membranes are summarized in the following points:

- In 1823, Dutrochet gave correct explanation of osmosis (passage of solvent across a membrane from low to high concentration) and dialysis (passage of solute across a membrane from high to low concentration).
- In 1867, Traube and Pfeffer performed one of the first quantitative studies on performance of artificial membranes.
- Moritz Taube, 1867, prepared the first synthetic membrane.
- In the late 1800's Graham discovered that arranging a membrane between a reservoir of pressurized air and another reservoir of unpressurized air could produce oxygen-enriched air.
- Early use of membranes was applied to recovery of NaOH by dialysis from wastewater containing hemicellulose from the viscose rayon industry.
- Also, uranium isotopes (235 and 238) are separated in the vapor phase through porous membranes.

For RO membranes, their history started with the following two studies:

- Reid and Breton, 1959, at the University of Florida developed cellulose acetate RO membranes.

- Loeb and Sourirajan, 1963, from the University of California, Los Angeles developed the first asymmetric cellulose acetate membrane, with higher salt rejection and water flux.

Subsequently, a huge amount of research studies were conducted with focus on development of new membrane materials and performance evaluation of these membranes. As for commercialization of the RO membranes it is summarized in the following points:

- In the late 1960s, the Gulf General Atomics and Aerojet General used Loeb-Sourirajan cellulose acetate membranes for constructing spiral wound modules.
- In 1971, Dupont introduced the Permasep B-9 permeator for BW desalination. The permeator contains millions of asymmetric aromatic poly amide (aramid) hollow fine fibers.
- In late 1973, Dupont introduced the Permasep B-10 permeator, also using asymmetric aramid fibers, capable of producing potable water from seawater in a single pass.
- In the mid-1970s, cellulose triacetate hollow fiber permeators were introduced by Dow Chemical Company, followed by Toyobo of Japan.
- During the same period. Fluid Systems and FilmTec introduced the spiral wound polyamide thin film composite membranes.
- Throughout the 1980s, improvements were made to these membranes to increase water flux and salt rejection with both BW and seawater.

- Today the predominate membrane materials are still aramids, polyamides, and cellulose acetate and triacetate in spiral wound and hollow fiber configurations.
- Applications of the RO membranes include potable water production, waste recovery, food applications, kidney dialysis, high-purity water for boiler feed, and ultrapure water electronics applications.
- In 2000, the RO technology was used to treat more than two billion gallons of water per day, and this market is expected to continue growing during the first half of the 21st century. [18]

3.3 RO Process Terminologies

The main terms used in the RO process are defined as follows:

- a) Recovery: It's the percentage of membrane system feed water that emerges from the system as product water or (permeate). Membrane system design is based on expected feed water quality and recovery is defined through initial adjustment of valves on the concentrate stream. Recovery is often fixed at the highest level that maximizes permeate flow while preventing precipitation of super saturated salts within the membrane system.
- b) Rejection: It's the percentage of solute concentration removed from system feed water by the membrane.
- c) Passage: It's the opposite of “rejection”; passage is the percentage of dissolved contaminants in the feed water allowed to pass through the membrane.
- d) Permeate: It's the purified product water produced by a membrane

system.

- e) Flow: Feed flow is the rate of feed water introduced to the membrane element or membrane system, usually measured in gallons per minute (gpm) or cubic meters per hour (m^3/h).
- f) Concentrate flow: is the rate of flow of non-permeated feed water that exits the membrane element or membrane system. This concentrate contains most of the dissolved constituents originally carried into the element or into the system from the feed source. It is usually measured in gallons per minute (gpm) or cubic meters per hour (m^3/h).
- g) Flux: It's the rate of permeate transported per unit of membrane area, usually measured in gallons per square foot per day ($\text{g}/\text{ft}^2\text{d}$) or liters per square meter per hour ($\text{L}/\text{m}^2\text{h}$). [13]

3.4 Factors Affecting Reverse Osmosis Performance

Permeate flux and salt rejection are the key performance parameters of a RO process. Under specific reference conditions, flux and rejection are intrinsic properties of membrane performance. The flux and rejection of a membrane system are mainly influenced by variable parameters including:

a. Pressure

With increasing effective feed pressure, the permeate TDS will decrease while the permeate flux will increase as shown in figure (3.5) [19].

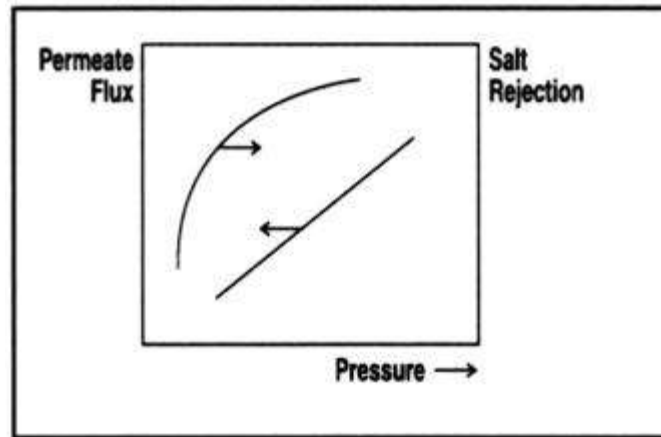


Figure (3.5): Pressure affecting the permeate flux and salt rejection. [19]

b. Temperature

If the temperature increases and all other parameters are kept constant, the permeate flux and the salt passage will increase as shown in figure (3.6) [19].

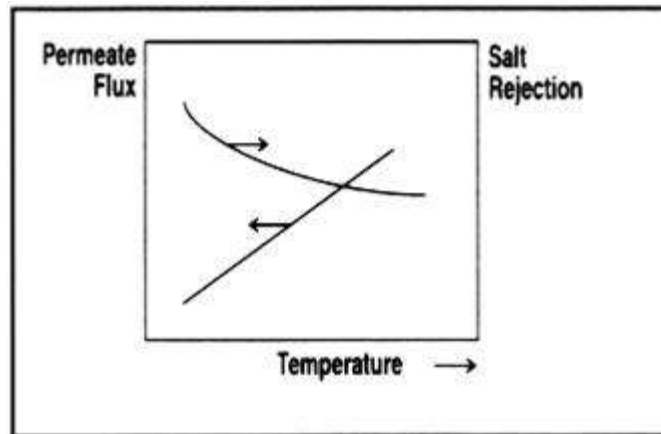


Figure (3.6): Temperature affecting the permeate flux and salt rejection. [19]

c. Recovery

In the case of increasing recovery, the permeate flux will decrease and stop if the salt concentration reaches a value where the osmotic pressure of the concentrate is as high as the applied feed pressure. The salt rejection will drop with increasing recovery as shown in figure (3.7) [19].

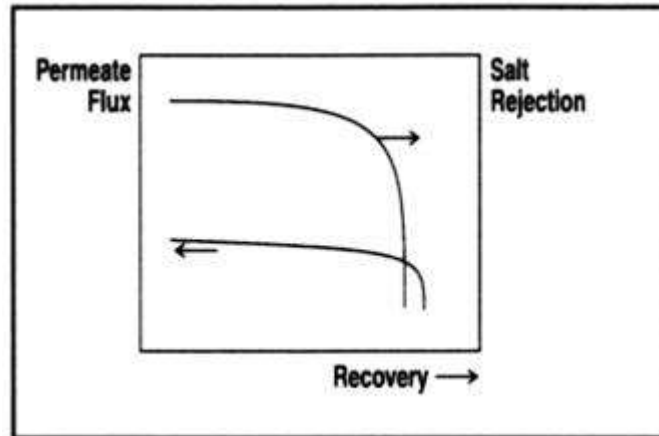


Figure (3.7): Recovery affecting the permeate flux and salt rejection. [19]

d. Feed water salt concentration

Figure (3.8) shows the impact of the feed water salt concentration on the permeate flux and the salt rejection [19].

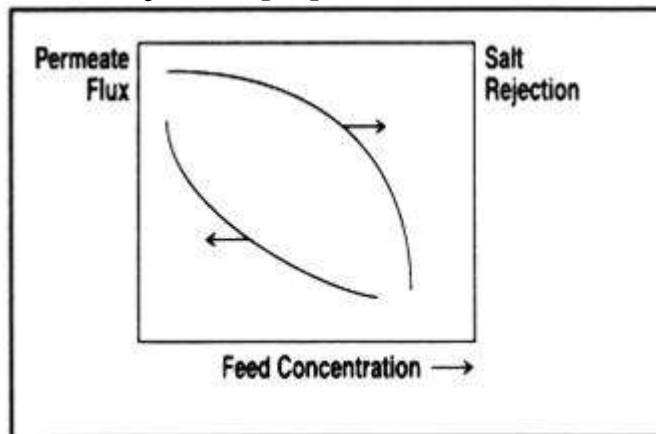


Figure (3.8): Feed water salt concentration affecting the permeate flux and salt rejection. [19]

And the following table summarizes previous figures of factors affecting RO performance,

Table (3.1): Factors affecting on the RO performance.

Factor	Permeate Flow	Salt Passage
Effective pressure	Increasing	Decreasing
Temperature	Increasing	Increasing
Recovery	Decreasing	Increasing
Feed salt concentrati	Decreasing	Increasing

3.5 Equations Used in Reverse Osmosis Process

There is a set of equations used to define the parameters governing transport across a membrane, and used in design RO system.

a. Osmotic pressure

The osmotic pressure (P_{osm}) of a solution can be determined experimentally by measuring the concentration of dissolved salts in solution:

$$P_{osm} = 1.19 (T + 273) \times \Sigma (mi) \quad (3.1)$$

Where P_{osm} = osmotic pressure (in psi), T is the temperature (in °C), and Σ (mi) is the sum of molal concentration of all constituents in a solution (in mol/L).

An approximation for P_{osm} may be calculated by assuming that 1000 mg/L of TDS equals about 0.76 bar of osmotic pressure. [20]

b. Flux

Flux is a term that describes in 3.3, there is a relationship between the water flux and the rate of fouling on an RO unit. A high flux rate causes the membrane to foul faster.

Once the flux rate is decided and the element area is known, the required number of elements can be calculated using Equation.[21]

$$\text{Number of Elements} = [\text{Permeate Flow (L/min)} \times 1440 \text{ min/day}] \div [\text{Flux (L/m}^2\text{day)} \times \text{Active Membrane Area (m}^2\text{)}]. \quad [21] \quad (3.2)$$

c. Water transport

The rate of water passage through a semipermeable membrane is defined in Equation (3.3).

$$Q_w = (\Delta P - \Delta P_{osm}) \times K_w \times S/d \quad (3.3)$$

where Q_w is the rate of water flow through the membrane, ΔP is the hydraulic pressure differential across the membrane, ΔP_{osm} is the osmotic pressure differential across the membrane, K_w is the membrane permeability coefficient for water, S is the membrane area, and d is the membrane thickness. This equation is often simplified to:

$$Q_w = A \times (NDP) \quad (3.4)$$

Where A represents a unique constant for each membrane material type, and NDP is the net driving pressure or net driving force for the mass transfer of water across the membrane. [20]

d. Salt transport

The rate of salt flow through the membrane is defined by equation (3.4):

$$Q_s = \Delta C \times K_s \times S/d \quad (3.5)$$

Where Q_s is the flow rate of salt through the membrane, K_s is the membrane permeability coefficient for salt, ΔC is the salt concentration differential across the membrane, S is the membrane area, and d is the membrane thickness. This equation is often simplified to:

$$Q_s = B \times (\Delta C) \quad (3.6)$$

Where B represents a unique constant for each membrane type, and ΔC is the driving force for the mass transfer of salts.

Equations (3.4) and (3.5) show that for a given membrane:

- Rate of water flow through a membrane is proportional to (NDP) differential across the membrane.
- Rate of salt flow is proportional to the concentration differential across the membrane and is independent of applied pressure.

Salinity of permeate, C_p , depends on the relative rates of water and salt transport through RO membrane:

$$C_p = Q_s/Q_w \quad (3.7)$$

The fact that water and salt have different mass transfer rates through a given membrane creates the phenomena of salt rejection. No membrane is ideal in the sense that it absolutely rejects salts; rather the different transport rates create an apparent rejection. The equations (3.3), (3.5), explain important design considerations in RO systems. For example, an increase in operating pressure will increase water flow without changing salt flow, thus resulting in lower permeate salinity. [20]

e. Salt passage

Salt passage is defined as the ratio of concentration of salt on the permeate side of the membrane relative to the average feed concentration. Mathematically, it is expressed in eq (3.8):

$$SP = (C_p/C_{fm}) \times 100\% \quad (3.8)$$

Where SP is the salt passage (in %), C_p is the salt concentration in the permeate, and C_{fm} is the mean salt concentration in feed stream.

Applying the fundamental equations of water flow and salt flow illustrates some of the basic principles of RO membranes. For example, salt passage is an inverse function of pressure; that is, the salt passage increases as applied pressure decreases. This is because reduced pressure decreases permeate flow rate, and hence, dilution of salt (the salt flows at a constant rate through the membrane as its rate of flow is independent of pressure). [20]

f. Salt rejection

Salt rejection is the opposite of salt passage, and is defined by Equation (3.9).

$$SR = 100\% - SP \quad (3.9)$$

Where SR is the salt rejection (in %), and SP is the salt passage as defined in Equation (3.8) [20]

g. Permeate recovery rate

Permeate recovery is another important parameter in the design and operation of RO systems. Recovery or conversion rate of feed water to product (permeate) is defined by Equation (3.10).

$$R = (Q_p/Q_f) \times 100\% \quad (3.10)$$

Where R is recovery rate (in %), Q_p is the product water flow rate, and Q_f is the feed water flow rate. The recovery rate affects salt passage and product flow. As the recovery rate increases, the salt concentration on the feed-brine side of the membrane increases, which causes an increase in salt flow rate across the membrane as indicated by Equation (3.5). Also, a higher salt concentration in the feed-brine solution increases the osmotic pressure, reducing the NDP and consequently reducing the product water flow rate according to Equation (3.3).[20]

h. Concentration polarization

As water flows through the membrane and salts are rejected by the membrane, a boundary layer is formed near the membrane surface in which the salt concentration exceeds the salt concentration in the bulk solution. This increase of salt concentration is called concentration polarization. The ef-

fect of concentration polarization is to reduce actual product water flow rate and salt rejection versus theoretical estimates. The effects of concentration polarization are as follows:

- a) Greater osmotic pressure at the membrane surface than in the bulk feed solution, ΔP_{osm} , and reduced NDP differential across the membrane ($\Delta P - \Delta P_{\text{osm}}$).
- b) Reduced water flow across membrane (Q_w).
- c) Increased salt flow across membrane (Q_s).
- d) Increased probability of exceeding solubility of sparingly soluble salts at the membrane surface, and the distinct possibility of precipitation causing membrane scaling.

The Concentration polarization factor (CPF) can be defined as a ratio of salt concentration at the membrane surface (C_s) to bulk concentration (C_b).

$$\text{CPF} = C_s / C_b \quad (3.11)$$

An increase in permeate flux will increase the delivery rate of ions to the membrane surface and increase C_s . An increase of feed flow increases turbulence and reduces the thickness of the high concentration layer near the membrane surface. Therefore, the CPF is directly proportional to permeate flow (Q_p), and inversely proportional to average feed flow (Q_{fav}).

$$\text{CPF} = K_p \times \exp(Q_p / Q_{\text{fav}}) \quad (3.12)$$

Where K_p is proportionality constant depending on system geometry. Using the arithmetic average of feed and concentrate flow as average feed flow, the CPF can be expressed as a function of the permeate recovery rate a of

membrane element (R_i). [20]

$$CPF = K_p \times \exp(2R_i/(2-R_i)) \quad (3.13)$$

3.6 Pretreatment of feed water

Pretreatment of feed water in RO system is necessary process to optimize system performance and prevent the three main problems associated with RO system; scaling, fouling, and degradation of RO membranes. These problems tend to decrease system productivity and performance.

3.6.1 Scaling

Scaling occurs when the sparingly soluble salts are concentrated within the element beyond their solubility limit as the water is removed and more dissolved ions are fed into the system. This leads to exceeding the solubility limit of most salts, causing a precipitate to form on the surface of the membrane. The precipitate reduces permeability and damages the membrane irreversibly. [22]

The most common sparingly soluble salts encountered are Calcium sulfate (CaSO_4), Calcium carbonate (CaCO_3), and silica. Other salts creating a potential scaling problem are Calcium fluoride (CaF_2), Barium sulfate (BaSO_4), Strontium sulfate (SrSO_4), and Calcium phosphate ($\text{Ca}_3(\text{PO}_4)_2$). And there is sparingly soluble inorganic compounds like Aluminum hydroxide ($\text{Al}(\text{OH})_3$), Aluminum phosphate (AlPO_4), Iron hydroxide ($\text{Fe}(\text{OH})_2$), Iron sulfide (FeS) and ... Etc. [13]

The indicators of saturation levels of sparingly soluble salts in the concentrate stream are the Langelier Saturation Index (LSI) and the saturation ratios. The LSI provides an indication of the calcium carbonate saturation.

Negative values of LSI indicate that the water is aggressive and that it will have a tendency to dissolve calcium carbonate. Positive values of LSI indicate the possibility of calcium carbonate precipitation. The LSI was originally developed by Langelier for potable water of a low salinity.

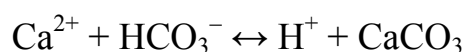
For high salinity water encountered in RO applications, the LSI is an approximate indicator only.

The saturation ratio is the ratio of the product of the actual concentration of the ions in the concentrate stream to the theoretical solubility's of the salts at a given conditions of temperature and ionic strength. These ratios are applicable mainly to sparingly soluble sulfates of calcium, barium and strontium. Silica could be also a potential scale forming constituent. Other potential scale forming salts, such as calcium fluoride or phosphate which may be present in RO feed, seldom represent a problem. [23]

Methods to minimize scaling:

a. Acid addition

Most natural surface and ground waters are almost saturated with CaCO_3 . The solubility of CaCO_3 depends on the pH, as can be seen from the following equation:



By adding H^+ as acid, the equilibrium can be shifted to the left side to keep calcium carbonate dissolved. Use food grade quality acid. To control calcium carbonate scaling by acid addition alone, the LSI in the concentrate stream must be negative. [13]

Acids, typically hydrochloric $[\text{HCl}]$ or sulfuric $[\text{H}_2\text{SO}_4]$, are injected into

the RO feed to lower pH. [24]

Sulfuric acid is used more often than HCl acid, because sulfuric acid is relatively lower in operating cost than HCl acid, and sulfuric acid is reduced fuming to the atmosphere, which means less corrosion to surrounding metal components, and there is a better membrane rejection of the sulfate ion than the chloride ion. [24]

This acids used to adjustments and make Scale Control for CaSO_4 , BaSO_4 , SrSO_4 . [13]

b. Scale inhibitor addition (antiscalants)

Scale inhibitors (antiscalants) can be used to control carbonate scaling, sulfate scaling, and calcium fluoride scaling. There are generally three different types of scale inhibitors, sodium hexametaphosphate (SHMP), organophosphonates and polyacrylates.

SHMP is inexpensive but unstable compared to polymeric organic scale inhibitors. Minor amounts adsorb to the surface of microcrystals, preventing further growth and precipitation of the crystals. Food grade quality SHMP should be used. Care must be taken to avoid hydrolysis of SHMP in the dosing feed tank. Hydrolysis will not only decrease the scale inhibition efficiency, but also create a calcium phosphate scaling risk. Therefore, SHMP is generally not recommended.

Organophosphonates are more effective and stable than SHMP. They act as antifoulants for insoluble aluminum and iron, keeping them in solution. Polyacrylates (high molecular weight) are generally known for reducing silica scale formation via a dispersion mechanism.

Polymeric organic scale inhibitors are also more effective than SHMP. Precipitation reactions may occur, however, with negatively charged scale inhibitors and cationic polyelectrolytes or multivalent cations (e.g., aluminum or iron). The resulting gum-like products are very difficult to remove from the membrane elements. For dosage rates on all antiscalants, contact the antiscalant manufacturers. Overdosing should be avoided. Make certain that no significant amounts of cationic polymers are present when adding an anionic scale inhibitor.

In RO plants operating on seawater with TDS in the range of 35,000 mg/L, scaling is not as much of a problem as in BW plants because the recovery of seawater plants is limited by the osmotic pressure of the concentrate stream to 30-45%. For safety reasons, however, a scale inhibitor is recommended when operating above a recovery of 35%. [13]

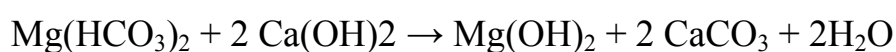
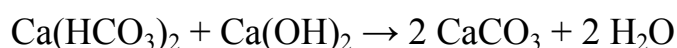
c. Softening with a strong acid cation exchange resin

In the ion exchange softening process, the scale-forming cations (is an ion with fewer electrons than protons, giving it a positive charge), such as Ca^{2+} , Ba^{2+} and Sr^{2+} , are removed and replaced by sodium cations. The resin is regenerated with NaCl at hardness breakthrough. The pH of the feed water is not changed by this treatment and, therefore, no degasifier is needed. Only a little CO_2 from the raw water is present that can pass into permeate, creating a conductivity increase there. The permeate conductivity can be lowered by adding some NaOH to the softened feed water (up to pH 8.2) to convert residual CO_2 into bicarbonate, which is then rejected by the membrane.

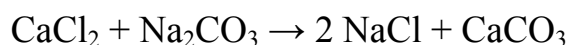
Softening with a strong acid cation exchange resin is effective and safe, provided the regeneration is done properly. It is used mainly in small- or medium-size BW plants, but not in seawater plants. [13]

d. Lime softening

Lime softening can be used to remove carbonate hardness by adding hydrated lime (Chemical name and formula: Calcium hydroxide Ca(OH)_2):



The noncarbonated calcium hardness can be further reduced by adding sodium carbonate Na_2CO_3 (soda ash):



The lime-soda ash process can also be used to reduce the silica concentration. With the hot lime silica acid removal process at 60–70°C, silica can be reduced to 1 mg/L by adding a mixture of lime and porous magnesium oxide. [13]

e. Preventive cleaning

In some applications, scaling is controlled by preventive membrane cleaning. This allows the system to run without softening or dosage of chemicals. Typically, these systems operate at low recovery in the range of 25%, and the membrane elements are replaced after 1–2 years. Accordingly, these systems are mainly small single-element plants for potable water. The simplest way of cleaning is a forward flush at low pressure by opening the concentrate valve. Short cleaning intervals are more effective than long cleaning times (e.g., 30 seconds every 30 minutes). [13]

f. Adjustment of operating variables

When other scale-control methods do not work, the operating variables of the plant have to be adjusted in such a way that scaling will not occur. The precipitation of dissolved salts can be avoided by keeping their concentration below the solubility limit. This is accomplished by reducing the system recovery until the concentrate concentration is low enough.

Solubility depends also on temperature and pH. In the case of silica, increasing temperature and pH increases its solubility. Silica is usually the only reason for considering adjustment of operating variables for scale control because these adjustments have economic drawbacks (energy consumption) or other scaling risks (CaCO_3 at high pH). [13]

3.6.2 Fouling

Fouling is the uneven accumulation of suspended or dissolved particles on the membrane surface or in the feed channel. The membrane surface becomes fouled when dissolved organic matter, dissolved solids, biogenic material and suspended particulate matter cling to it as they get separated from the water. Fouling leads to significant problems such as loss of flux, salt passage through the membrane, pressure drop across membrane modules, increase in contamination of permeate, degradation of the membrane material, and reduction in membrane life [22].

The common indicators of suspended particles used in the RO industry are turbidity and Silt Density Index (SDI).

Turbidity is an indicator for the rate of RO membrane fouling. Turbidimeters (also called nephelometers) measure the scattering of light

caused by various suspended solids in the water sample. Water samples having turbidity reading greater than 1 will tend to foul the membranes. These readings are typically given in nephelometric turbidity units (NTU). [25]

SDI: Also known as the Fouling Index (FI) is a good guide line to determine the fouling potential of RO feed water. The guidelines for RO operation using the SDI is as follows:

- $SDI < 1$; implies high quality feed water that would provide trouble free operation for years.
- $1 < SDI < 3$, implies moderate to low quality feed water that would allow for few months of operation before need for membrane cleaning.
- $3 < SDI < 5$ implies low quality feed water, which would require frequent cleaning.
- $SDI > 5$ implies very poor water quality and operation at these conditions is not acceptable. [18]

For long-term reliable operation of the RO unit, the average values of turbidity and SDI in the feed water should not exceed 0.5 NTU and 2.5 SDI units, respectively [23].

Methods to minimize fouling:

a. Screening / Preclarification

Preliminary treatment is used when a water source contains coarse debris such as gravel, sand, and grit. Removal of these large particles prevents equipment damage and overburden of downstream treatment processes.

Three commonly used pretreatment methods include screening, presedimentation, and microstraining.

Screens and bar racks are physical processes that are usually located at the intakes of rivers, lakes, and reservoirs for water treatment plants. The type and size of screens depends on the location where the raw water is collected. When water is withdrawn from the surface of a river, coarse screens of 3 inches or larger are used. For a submerged intake from a reservoir or lake, smaller coarse screens can be used.

Presedimentation is used to remove gravel and sand, which can jam equipment and wear down pump impellers, as well as silt, which causes increased loads on the coagulation and sedimentation processes. Presedimentation systems are intended to remove up to 60% of settleable material.

Microstraining utilizes a fine screen to reduce suspended solids from raw waters that contain high concentrations of algae, other aquatic organisms, and small debris that can clog filters. It is usually made from a fine fabric or screen that is wound around a drum. The drum, which is usually 75% submerged, rotates in a circle as water flows from the inside to the outside of the drum. The thin fabric collects the debris as the water passes through the drum. The openings in the microstrains vary from 20 to 60 microns. This process removes suspended solids but not bacteria. The solid deposits are removed by water jets, which force the deposited material into a channel where they are then collected. [26]

b. Coagulation / Flocculation

Coagulation and flocculation are used in conjunction to precipitate dissolved species and aggregate them in water. Coagulation is a chemical process in which the negatively charged particles in water are destabilized and dissolved organics are precipitated. In this process, a coagulant of opposite charge to the suspended solids is added to the water to neutralize these charges. Coagulant aids can also be utilized to increase the density of aggregates, thus reducing the settling time of the flocs and adding strength in order to prevent them from breaking apart in subsequent stages. The optimum type and dosage of coagulant is crucial, and can be determined through bench-scale experiments and jar tests. Table (3.2) lists common coagulants and coagulant aids.

Table (3.2): Lists of common coagulants and coagulant aids.

Chemical Name	Chemical Formula	Primary Coagulant	Coagulant Aid
Aluminum sulfate (Alum)	$\text{Al}_2(\text{SO}_4)_3 \cdot 14 \text{H}_2\text{O}$	X	
Ferrous sulfate	$\text{FeSO}_4 \cdot 7 \text{H}_2\text{O}$	X	
Ferric sulfate	$\text{Fe}_2(\text{SO}_4)_3 \cdot 9 \text{H}_2\text{O}$	X	
Ferric chloride	$\text{FeCl}_3 \cdot 6 \text{H}_2\text{O}$	X	
Cationic polymer	Various	X	X
Calcium hydroxide (Lime)	$\text{Ca}(\text{OH})_2$	X*	X
Calcium oxide (Quicklime)	CaO	X*	X
Sodium aluminates	$\text{Na}_2\text{Al}_2\text{O}_4$	X*	X
Bentonite	Clay		X
Calcium carbonate	CaCO_3		X
Sodium silicate	Na_2SiO_3		X
Anionic polymer	Various		X
Nonionic polymer	Various		X

* Used as a primary coagulant only in water softening processes.

Rapid mixing is used to evenly distribute the coagulant throughout the water. In a study on optimization of a coagulation-flocculation treatment by Rossini et al. (1998), optimal results could be obtained with both short (about 10 s) and long (60 or 90 s) mixing times. Rapid mixing is followed by flocculation, a gentle mixing stage that facilitates collisions between particles. Flocculation is thus a physical process to enhance opportunities for particle collisions, allowing particles to aggregate together to form larger floc. These processes are then followed by a solid-liquid separation process to remove the solids formed. [22]

c. Clarification

Clarification processes remove particles due to density differences between the particles and water. Water is pumped to a tank with quiescent conditions, and over the course of the process, heavier particles settle down to the bottom of the tank. Once these solids build up, they are removed and processed elsewhere. Water is drawn from the top of the tank where it is free from larger particles, and moves on for further treatment.

An alternative clarification process is dissolved air flotation, in which particles are separated by floating them to the surface with micro sized air bubbles. The particles are then removed by laterally sweeping the water on the bottom and the particles from the surface in opposite directions. This technique is advantageous since it can remove small and low density particles because the particles are not required to settle. In addition, algae and oil can easily be removed with this process. In some cases, clarification or sedimentation is bypassed and the water is filtered immediately after floc-

culation. [22]

d. Media Filtration (MEF)

MEF is a process in which water passes through a column or a bed of media such as sand, anthracite, or other materials in order to remove solids. Particle removal is a physical process, where matter is separated from water by attaching to the filter medium [22].

MEF is suggested when the SDI value is greater than 3 or when the turbidity is greater than 0.2 NTU. There is no exact rule, but the above guidelines should be followed to prevent premature fouling of RO membranes [28].

MEF that uses a coagulant addition can remove particulates down to 5-10 microns [27].

There are three main design criteria that can be altered to fit the specific needs of the application in which the filter is used. These include media configuration, direction of flow, and method of moving water through the filter, either by gravity or by pressure. The configuration of the media bed can have one media (mono media) or two media with the coarser material set on top of a finer material (dual media). Multi-media filters with three media types are also possible. The selection and number of media used vary by application and need. Some commonly used media and their characteristics are listed in table (3.3) [22].

Table (3.3): Filter medias and their most common uses.

Media	Color	Most Common Use
Activated Carbon	Black	Removing chlorine and organic contaminants, color and taste removal
Anthracite	Black	Removing turbidity
Birm	Black	Removing dissolved iron and manganese compounds.

Filter"AG"	Light gray	Removing normal suspended solids down to 20-40 micron range.
Filter Sand	Light brown	Removing coagulum or precipitates containing impurities.
Garnet	Reddish black	Application where chemical and abrasive resistance are necessary.
Manganese Greensand	Purple black	Removing soluble iron, manganese, Hydrogen sulfide, radium, arsenic.
MTM	Dark brown	Reducing iron, manganese, hydrogen sulfide.
Northern Ultra	Pale green	Same as filter sand above.
Support Graval	Multicolor	Supporting the primary filter medium.
Zeobest	Pale green	Removing turbidity down to 3 microns.
Zeobest Ultra	Pale green	Same as Zeobest with a capacity to absorb ammonia ions.

The following figure shows pictures for some medias used in Filtration.



Figure (3.9): Pictures for some medias used in MMF.

The flow in media filters can vary between up-flow and down-flow designs. In an up-flow filter, water is distributed evenly in the bottom of the tank and flows upward through the media in a swirling motion. In a down-flow filter, the water is distributed evenly across the top of the media and moves downward through the filter. An up-flow filter design has some unique advantages. As the water moves in an upward swirling motion, it is constantly lifting the media, which regenerates the bed eliminating the need for backwashing [22].

The way in which water flows through a media filter can be altered: either

via gravity or pressure. Pressure filters are often selected for use because of their competitive costs, efficient use of space and their ease of installation and operation when compared to media gravity filters [22].

Figure (3.10) shows a diagram of a down flow sand gravel multimedia pressure filter.

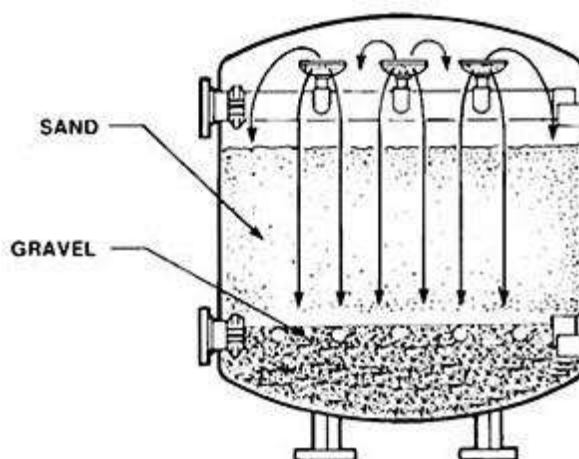


Figure (3.10): Diagram of a down flow MMF.

e. Activated Carbon Filter (ACF)

ACF is used for both removing organic constituents and residual disinfectants (such as chlorine and chloramines) from water. ACF media is made from coal, nutshells or wood. Activated carbon removes residual chlorine and chloramines by a chemical reaction that involves a transfer of electrons from the surface of the ACF to the residual chlorine or chloramines. The chlorine or chloramines ends up as a chloride ion that is no longer an oxidizer.

The disadvantage of using an ACF before the RO unit is that the ACF will remove chlorine quickly at the very top of the ACF bed. This will leave the remainder of the ACF bed without any biocide to kill microorganisms. An

ACF bed will absorb organics throughout the bed, which is potential food for bacteria, so eventually an ACF bed can become a breeding ground for bacteria growth which can pass easily to the RO membranes. Likewise, an ACF bed can produce very small carbon fines under some circumstances that have the potential to foul an RO. [27]

f. Cartridge filters (CF)

A CF with an absolute pore size of less than 10 μm is the suggested minimum pretreatment required for every RO system. It is a safety device to protect the membranes and the HP pump from suspended particles. Usually it is the last step of a pretreatment sequence.

The filter should be sized on a flow rate according to the manufacturer's recommendation and replaced before the pressure drop has increased to the permitted limit [13].

The main types of cartridge filters are:

a. Melt blown (Solid) CF

A melt blown filter cartridge is a "depth" type filter that is good for the removal of relatively uniform sized particles throughout the body of the filter, not just on the surface. It removes particles ratings from 1-75 microns. Melt blown CF is particularly effective on well waters and normal city water.

The standard 10", 5-micron, melt blown filter cartridge is the least expensive and most widely used filter cartridge on the market today. The melt blown 5-micron cartridge is used extensively for both commercial and domestic applications.

- Typical applications include:

- 1 to 50 micron filters used in general purpose applications, with the 5-micron cartridge being the most popular.
- 5 micron filters installed up-stream of ion exchange resin columns to remove particles and down-stream to remove resin fines that could pass through under drains and plug a pure water system.
- 5-micron pre-filters installed ahead of a RO system to remove particles that could plug up membranes and deteriorate performance. [28]



Figure (3.11): Melt blown (Solid) CF.

b. String Wound CF

The string wound cartridge was the original CF element. It is a “surface” type filter that is effective in removing diverse sized particles. “This filter removes particles ratings from 0.5-150 microns” [29]. Because of the overlapping nature of the string windings, it has an effective surface area considerably larger than that of the melt blown filter. String wound filters are particularly applicable to surface waters from streams and rivers [28].

While string wound cartridges predate all the other filters, with polypropylene fiber construction, a string wound is still a good general-purpose filter

and in certain applications, the best choice. Like the melt blown filter cartridge, string wound cartridges are inexpensive. In its 10", 5-micron form it is the 2nd most commonly used filter cartridge on the market and is used extensively in pre-filtration applications [28].

- Typical applications include:
 - 1 to 50 micron filters used in general purpose applications.
 - 5-micron filters installed up-stream of ion exchange resin columns to remove particles and down-stream to remove resin fines that could pass through under drains and clog a pure water system.
 - 5-micron pre-filters installed ahead of a RO system to remove non-uniform sized particles [28].



Figure (3.12): String Wound CF.

c. Pleated CF

A pleated cartridge is a surface type filter cartridge that is effective in removing diverse sized particles in limited quantities. “Pleated cartridges will remove particles up to 50 micron” [29]. Pleated CF is particularly effective on surface waters from streams and rivers.

Pleated CF is constructed to provide a surface area far in excess of the diameter of the filter [28].

The micron rating of a pleated filter is more precise than either the melt blown or string wound cartridges. Though pleated cartridges are more expensive than melt blown or string wound, they are the only choice for sub-micron filtration. (0.45 to 0.1 microns) Sub-micron pleated filter cartridges are used extensively as biological blocks in the production of high-purity and sterile water [28].

- Typical applications include:
- 5-micron general-purpose filters used before and after ion exchange resin columns.
- 1 to 50 micron filter on the vent of a water storage tank to help prevent airborne particles from entering the tank during draw down in non-critical applications.
- 0.45 sub-micron post-filters installed after ion exchange systems act as final filters for particle sensitive applications.
- 0.2 sub-micron post-filters are installed after ion exchange and ultra-violet sterilization systems to act as final filters yielding bacterial and particle counts of near zero.

- sub-micron hydrophobic filters are used extensively on the vents of a high-purity water storage tanks to prevent airborne dust and micro-organisms from entering the tank during draw down in critical applications.
- to 0.2 sub-micron “Absolute” filters for both system and point of use filtration in critical applications. [28]



Figure (3.13): Pleated CF.

d. Media CF

A Media CF is not like the mechanical filters described above. A media cartridge is actually a water treatment device that effects chemical changes in the water. The flow rate through a media cartridge is substantially lower than that similarly sized particles filter. For example a 10” 5-micron filter can flow at 5 GPM, while the same sized Carbon Media cartridge flow rate should be less than 2.5 GPM. (Depending on chlorine and organic loading). Replacement of media cartridges is not dictated by pressure drop. Carbon media cartridge replacement should be scheduled for every three months or more often.

- Typical applications include:

- Activated Carbon for the removal of chlorine, taste and odor.
- Mixed Bed DI resin for water purification.
- Calcite media for neutralization of acidic water.
- Many other medias are available to handle a wide variety of water problems. [28]



Figure (3.14): Media CF.

3.6.3 Membrane degradation

It is the final problem associated with RO system. It occurs when the membranes are exposed to conditions that destroy the polymers used to create the membranes. Some membranes are susceptible to hydrolysis at high and low pH, while others are degraded by exposure to oxidizers such as chlorine. To prevent membrane degradation by acidic or alkaline waters, a corrective amount of acid or base should be added to the feed water to make the pH approximately neutral. To prevent oxidation reactions, dechlorination (Removal of chlorine from feed water) is used.

3.7 RO Membrane Modules

The practical equipment where the actual membrane based separation occurs is known as membrane modules. The basic aim of development of these modules is to provide maximum membrane area in relatively smaller volume, so that the permeate flux i.e., the productivity of the system is maximum.

3.7.1 Types of membrane modules

The four more commonly membrane modules used are:

- a) Plate and frame module.
- b) Hollow fiber module.
- c) Spiral wound module.
- d) Tubular modules.

Each of these modules is described below:

a. Plate and frame modules

The heart of plate-frame module is the support plate that is sandwiched between two flat sheet membranes. The membranes are sealed to the plate, either gasket with locking devices, glue or directly bonded. The plate is internally porous and provides a flow channel for the permeate which is collected from a tube on the side of the plate. Ribs or grooves on the face of the plate provide a feed side flow channel. The feed channel can be a clear path with channel heights from 0.3 to 0.75 mm. The higher channel heights are necessary for high viscosity feeds; reduction in power consumption of 20% to 40% can be achieved by using a 0.6 mm channel compared to a 0.3 mm channel. Alternatively, retentive separator screens (20 or 50 mesh pol-

polypropylene) can be used. Commercial plate-frame units are usually horizontal with the membrane plates mounted vertically. They can be run with each plate in parallel plates in two or three series. Laboratory is also available as preformed stacks up to 10 plates [30]. Packing density (membrane surface area per module volume m^2/m^3) is about 100-400 m^2/m^3 , this module is resistant to fouling (when membrane has low packing density then it has high resistant to fouling) this makes it expensive and used primarily for highly fouling feeds.[31] A typical plate and frame module is shown in figure (3.15):

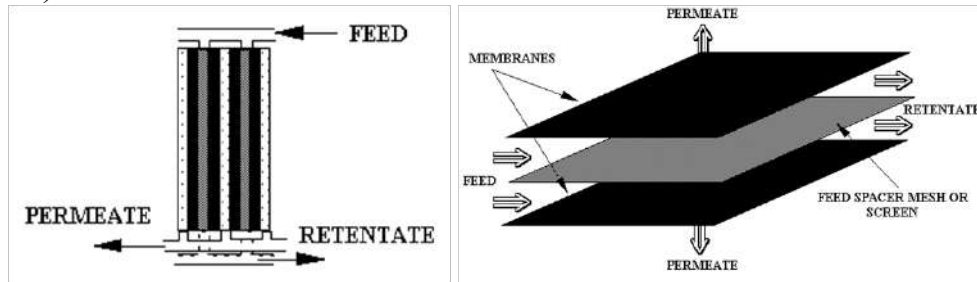


Figure (3.15): Plate and frame module. [32]

b. Tubular modules

The membrane is cast on the inside surface of a porous tube. Tubular membranes operate in tangential, or cross-flow, design where process fluid is pumped along the membrane surface in a sweeping type action. The feed solution is pumped through the center of the tube at velocities as high as 6 m/s. These cross-flow velocities minimize the formation of a concentration polarization layer on the membrane surface, promoting high and stable flux and easy cleaning, especially when the objective is to achieve high suspended solids in the MF, UF or NF concentrate. Permeate is driven through the membrane to be directed out of the system or back into the process de-

pending on the application. There are many advantages in tubular membrane configurations. Besides their hard construction, they have a distinct advantage of being able to process high suspended solids, and concentrate product successfully and repeatedly to relatively high end point concentration levels without plugging. A common objective of an end-of-pipe waste treatment UF system is to reduce waste volume as much as possible to reduce concentrate hauling costs. For juice clarification applications, tubular membrane systems produce the greatest yields and the highest final suspended solids concentration levels. Tubular MF, UF and NF systems do not require significant prefiltration. Some tubular products have the ability to be mechanically cleaned with sponge balls. Sponge balls can be used in process, and are also used to enhance chemical cleaning by reducing time and cleaning chemicals. Tubular membranes are ideally suited to treatment of metal working oily waste, wastewater minimization and recovery from industrial processes, juice clarification, treatment of pulp and paper industry waste, etc. Tubular membranes typically have life up to 2 to 10 years [30]. Packing density $< 300 \text{ m}^2/\text{m}^3$, the modules have a low packing density and can be expensive to operate because of the high feed flow rates necessary, then it used primarily for highly fouling feeds [31]. Figure (3.16) shows some tubular membranes.



Figure (3.16): Different figures of tubular modules. [32]

c. Hollow fiber module

In hollow fiber module, lots of hollow fibers (each fiber is a tubular module, with an outer diameter up to $200\ \mu\text{m}$) are kept in a large pipe. Geometry allows a high membrane surface area to be contained in a compact module. This means large volumes can be filtered, while utilizing minimal space, with low power consumption. Hollow fiber membranes can be designed for circulation, dead-end and single pass operation. Some of the many hollow fiber membrane filtration applications include; potable water treatment, juice clarification, dairy processing etc. The advantages of such modules include reduction in space requirement, lowering in labor cost, lowering in chemical cost, delivery of high quality product water, etc. Hollow fiber membranes offer the unique benefits of high membrane packing

densities, sanitary designs and, due to their structural integrity and construction, can withstand permeate back pressure thus allowing flexibility in system design and operation [30]. The Highest Packing Density up to $30,000 \text{ m}^2/\text{m}^3$, these elements have an extremely high packing density and so can have high permeate production rates per module. However, these modules are highly prone to fouling and so are not feasible for some applications [31]. Figure (3.17) is to hollow fiber module.

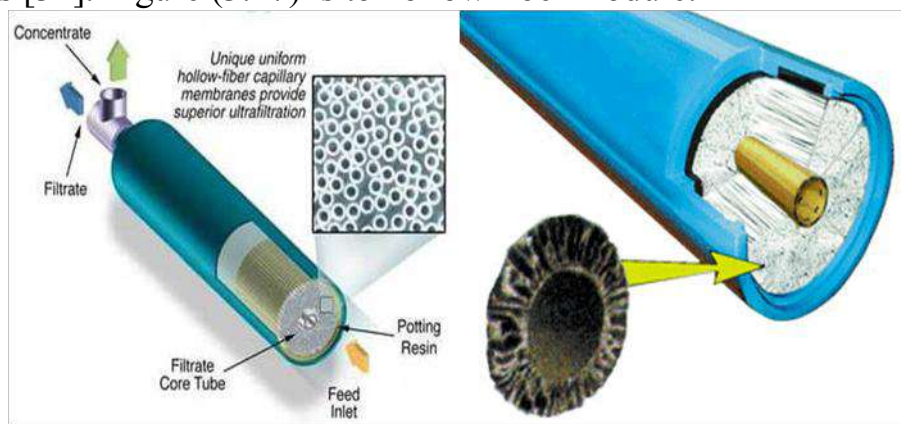


Figure (3.17): Hollow fiber module. [32]

d. Spiral wound module

In spiral wound membrane, membrane is cast as a film onto flat sheet. Membranes are sandwiched together with feed spacers (typical thickness 0.03 to 0.1 inch) and permeate carrier. They are sealed at each edge and wound up around a perforated tube. The module diameter ranges from 2.5 to 18 inch and length varies from 30 to 60 inch. The application of spiral wound module includes, seawater desalination, BW treatment, potable water treatment, dairy processing, electro coat paint recovery, protein separation, etc [30]. Packing density of it is ($300\text{-}1,000 \text{ m}^2/\text{m}^3$), This type of element has a high packing density, moderate fouling resistance, and lower

capital and operating costs compared to plate-and-frame or tubular modules [31].

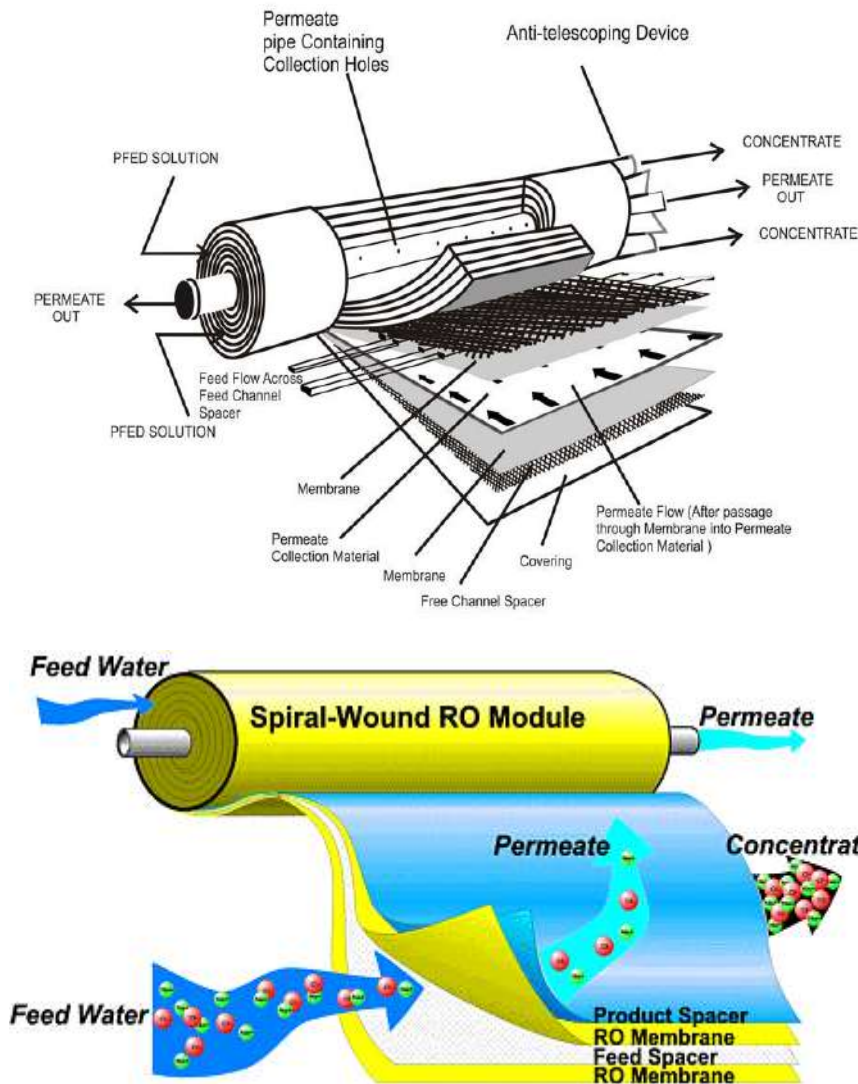


Figure (3.18): Spiral wound module [30].

3.7.2 Comparison between membrane types

a. Based on membrane processes

Table (3.4) shows that membrane types is very appropriate, or appropriate, or not appropriate to use with membrane processes.

Table (3.4): Comparison between membrane types based on membrane processes. [32]

Operation	Module		
	Tubular	Spiral-wound	Hollow fiber
Reverse Osmosis	A	VA	VA
Ultrafiltration	VA	A	NA
Microfiltration	VA	NA	NA

VA = Very appropriate; A = Appropriate; NA = Not appropriate.

b. Based on some membrane types specification

Table (3.5) shows comparison between membrane types based on channel spacing, packing density, energy costs, particulate plugging, and ease of cleaning.

Table (3.5): Comparison between membrane types based on some specifications [33].

Module configuration	Chanel spacing (cm)	Packing density ² ₃ (m ² /m ³)	Energy costs (pumping)	Particulate plugging	Ease of cleaning
Hollow fiber	0.02-0.25	1200	Low	high	fair
Tubular	1.0- 2.5	60	High	low	excellent
Flat plate	0.03-0.25	300	Moderate	moderate	good
Spiral wound	0.03-0.1	600	Low	very high	poor-fair

3.7.3 Pressure vessel

Pressure vessel: It's a stand supporting number of membranes (from 1 to 8) installed in it, these membranes connected in series by interconnecting piping, pressure vessel has permeate ports, located in center of the end plate, and feed and concentrate ports, located on the opposite ends of the vessel.

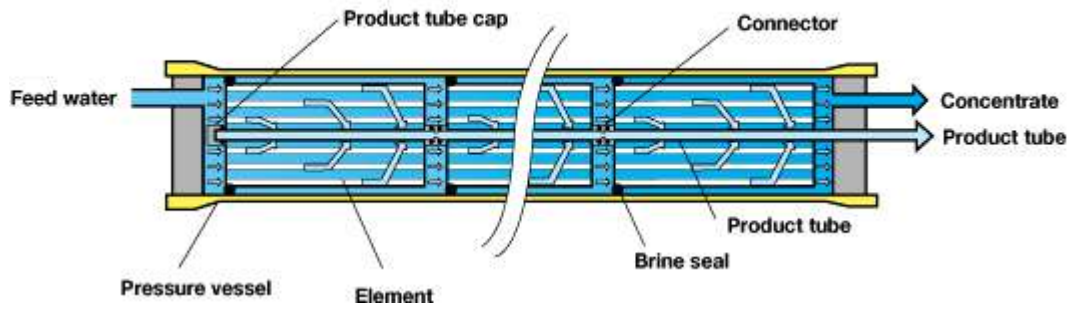


Figure (3.19): Pressure vessel.

3.8 Design of RO System

There are many options for designing of RO systems which depend on the goal of the system. The following sections shows the different main options for design RO systems, RO system may be one of the following options or combined between this options.

This thesis depends on ROSA from DOW Chemicals Company to design RO system in Az Zubeidat village as case study in West Bank (this system exists and works in this village).

3.8.1 Single pass RO system type

Single-module systems are chosen when only one or a few membrane elements are needed for the specified permeate flow as shown in figure (3.20).[13]

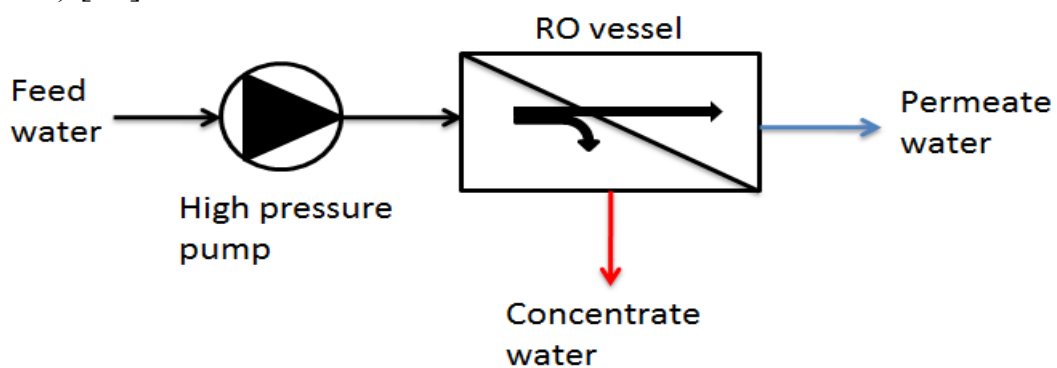


Figure (3.20): Single Pass RO system.

3.8.2 Double pass RO system type

A double pass system is the combination of two RO systems where permeate of the first system (first pass) becomes the feed for the second system (second pass). This type used to improve permeate quality, and allows the opportunity to remove CO_2 gas from permeate by injecting caustic between the first and second pass [27].

CO_2 is undesirable when you have mixed ion exchange resin beds after the RO. By adding caustic after the first pass, you increase the pH of the first pass permeate water and convert CO_2 to bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) for better rejection by the RO membranes in the second pass. This can't be done with a single pass RO because injecting caustic and forming carbonate (CO_3^{2-}) in the presence of cations such as calcium will cause scaling of the RO membranes [27].

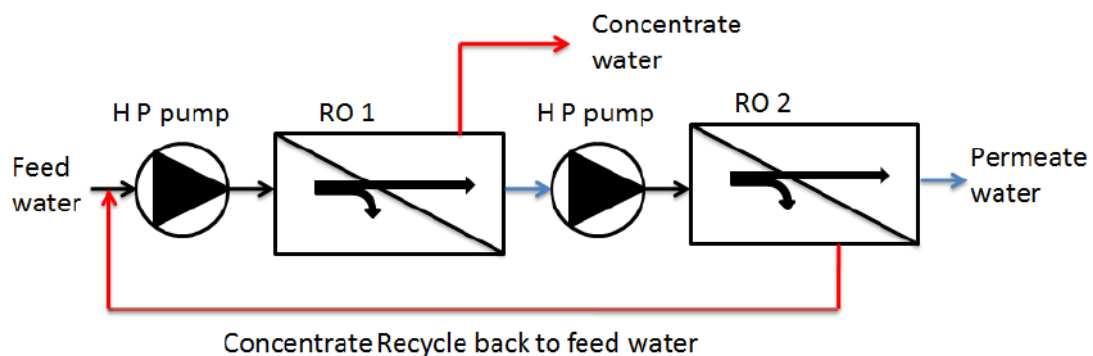


Figure (3.21): Double pass RO system type.

As shown in figure (3.21), the concentrate of RO2 could be recycled back to the feed of RO1, because its quality is usually better than the system feed water [25].

The feed of RO2 is a high quality (RO1 permeate), thus RO2 can be de-

signed for a higher recovery than RO1 and with fewer membrane elements [25].

Instead of having a separate HP pump for the second pass, the whole system can also be operated with one single HP pump, provided the maximum permissible feed pressure of the membrane element is not exceeded (41 bar for BW elements), the second pass is then operated with the permeate backpressure from RO1[25].

3.8.3 Single stage RO system

In a one stage RO system two or more pressure vessels are arranged in parallel, the feed water enters the RO system as one stream and exits the RO as either concentrate or permeate water as shown in figure (3.22) [25].

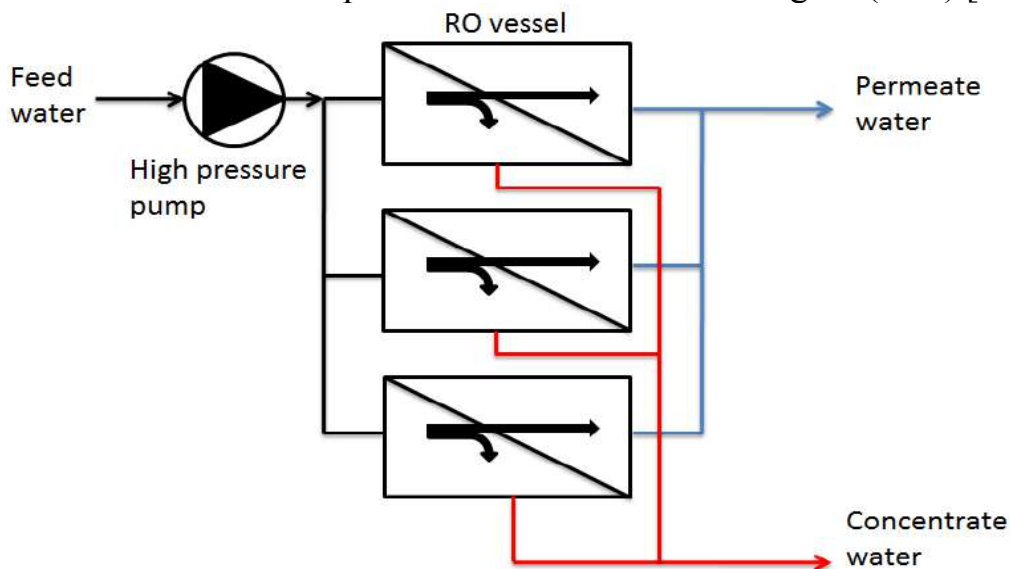


Figure (3.22): Single stage RO system.

3.8.4 Double stage RO system

In a double stage system the concentrate from the first stage becomes the feed water to the second stage. The permeate water is collected from the first stage is combined with permeate water from the second stage, this type

used to increase the recovery of the system, A typical double stage system using a staging ratio of 2:1 is shown in figure (3.23). The staging ratio is defined as the ratio of pressure vessels in two adjacent arrays, upstream vessels and downstream vessels [25].

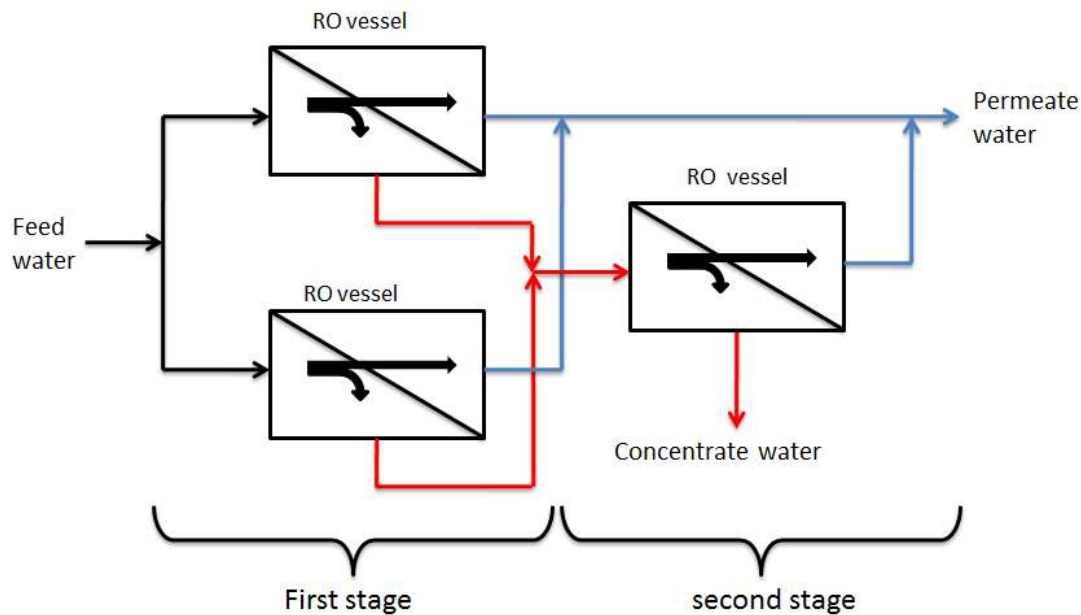


Figure (3.23): Double stage RO system.

3.9 RO cleaning

RO membranes will inevitably require periodic cleaning, anywhere from 1 to 4 times a year depending on the feed water quality. As a general rule, if the normalized pressure drop or the normalized salt passage has increased by 15%, then it is time to clean the RO membranes. If the normalized permeate flow has decreased by 15% then it is also time to clean the RO membranes. You can either clean the RO membranes in place or have them removed from the RO system and cleaned off site by a service company that specializes in this service. It has been proven that offsite membrane cleaning is more effective at providing a better cleaning than onsite clean-

ing skids.

RO membrane cleaning involves low and high pH cleaners to remove contaminants from the membrane. Scaling is addressed with low pH cleaners and organics, colloidal and biofouling are treated with a high pH cleaner. Cleaning RO membranes is not only about using the appropriate chemicals. There are many other factors involved such as flows, water temperature and quality, properly designed and sized cleaning skids and many other factors that an experienced service group must process in order to properly clean RO membranes. [27]

Chapter Four

Solar Energy in Palestine

Introduction

Palestine locates between the longitude meridian 34.15° and 35.40° east and between the latitude circle 29.30° and 33.15° North, The area of Mandate Palestine is 27000 Km^2 , it consists of two separated areas from one another. The West Bank which extends from the Jordan River to the center of Palestine, the area of it is about 5900 Km^2 , and the Gaza Strip is located on the western side of Palestine adjacent to the Mediterranean Sea, the area of it is about 365 Km^2 . [34]

The atmosphere of Palestine is clear and its air is pure. Summer temperatures reach 35° centigrade and in the winter temperature may drop to Zero. The rainy season starts in the second half of autumn. (Mid-October) and continues until the end of April. Heavy rain is, however, limited to fewer than 50 days, with around 70% of the rain falling during November to February. The country is influenced by the Mediterranean Sea breeze that comes around mid-day. However, the country is affected by annual waves of hot, dry, sandy and dust Khamaseen winds which originate from the Arabian Desert during the months of April, May and mid-June [35].

The average annual relative humidity is 60% and reaches its highest rates during the months of January and February. In May, however, humidity levels are at their lowest. Night dew may occur in up to 180 days per year [35].

4.1 Potential of Solar Energy in Palestine

Palestine has one of the highest solar energy potential of all countries of the world. It enjoys over 2800 sunshine hours every year, with an annual average daily solar radiation intensity amounting to $5.4 \text{ kWh/m}^2\text{-day}$ [36].

Table (4.1): Monthly average solar radiation (kWh/m²-day) in Az Zubeidat village-Jordan valley. [36]

Month	(kWh/m ² -day)
January	3.01
February	3.38
March	5.05
April	6.7
May	7.05
June	8.34
July	7.69
August	7.29
September	5.92
October	4.65
November	3.28
December	2.65

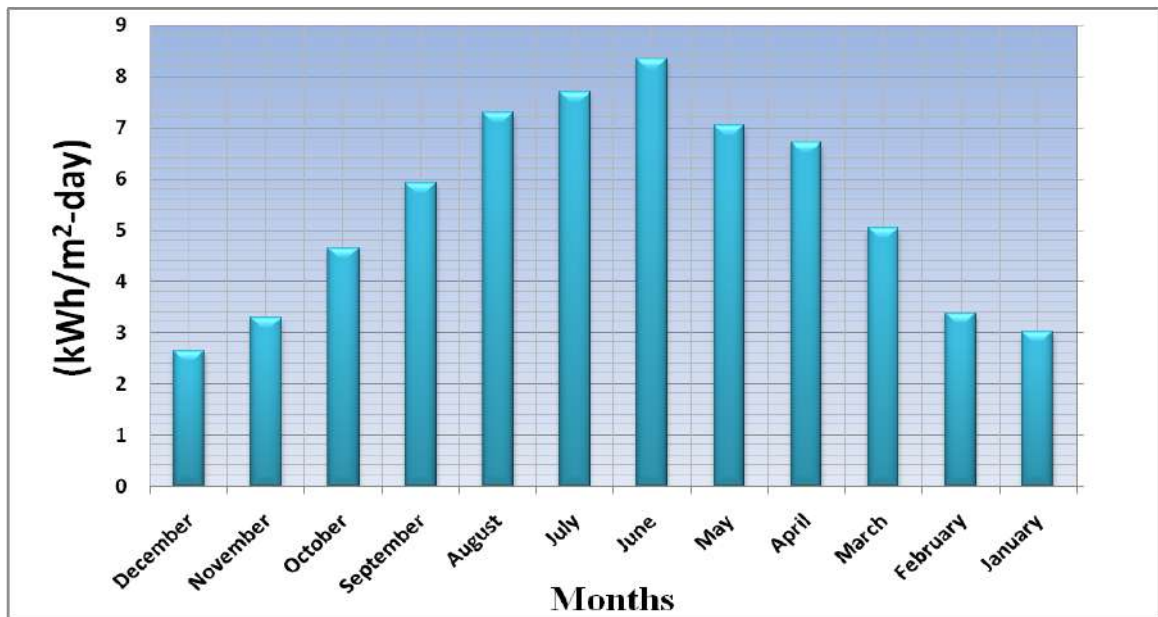


Figure (4.1): Monthly average solar radiation in Az Zubeidat village-Jordan valley.

Data in table (4.1) have been measured in almaleh village, the horizontal distance between almaleh and Az Zubeidat village about 18 km, and within 50 km distance the data don't change, therefore these data are dependable to a Az Zubeidat village. Measurements in a Az Zubeidat village isn't

complete until now (solar radiation must be measured at least one year) [37].

Data in table (4.1) have been measured on horizontal surface, the PV arrays in Az Zubaidat system was built on tilted angle equal to 45° , Nevertheless these data are dependable to a Az Zubeidat village because the global solar radiation is in general given all over the world for horizontal surfaces, sometimes the direct and diffused are available also for the horizontal surfaces. Taking into consideration that the annual total global solar radiation on a surface with tilted angle equal to the latitude on the location is approximately equal to the annual total global solar radiation on horizontal surface, since our system was tilted on 45° where the deviation from the latitude (32°) is not too much, therefore the total average global solar radiation on this tilted angle will not different from horizontal surface, in addition the small deviation in the average solar radiation is compensated in safety factor on the design.[37]

From table (4.1) peak sunshine hours (the number of equivalent hours per day that solar irradiance is at its peak level of 1 kW/m^2) for every month can be calculated as follows:

The average Peak Sun Hours around month (PSH_m):

$\text{PSH}_m = \text{Esd}/G_o$ where:

Esd: the average daily solar radiation intensity for a month,

G_o : the peak solar radiation intensity = 1000 W/m^2 .

For example PSH_m in January = $3010/1000 = 3.01 \text{ hour}$.

PSH: The average Peak Sun Hours around the year is calculated as:

$\text{PSH} = \text{sum} (\text{PSH}_m)/12$

$$\text{PSH} = \frac{(3.01+3.38+5.05+6.7+7.05+8.34+7.69+7.69+7.29+5.92+4.65+3.28+2.65)}{12}$$

$$\text{PSH} = 65.01/12 = 5.4 \text{ h.}$$

The following table shows hourly average solar radiation of typical summer day (20/7/2012), this measurement was obtained from the measuring system in Az Zubeidat project.

Table (4.2): Hourly average solar radiation in Az Zubeidat village, for the day (20/7/2012).

Hours	Solar Radiation(W/m ²)	Hours	Solar Radiation(W/m ²)
01:00	0	13:00	712.5
02:00	0	14:00	615.4
03:00	0	15:00	486.2
04:00	0	16:00	337.4
05:00	0.566	17:00	172.56
06:00	45.599	18:00	60.8
07:00	169.76	19:00	8
08:00	336.28	20:00	0
09:00	509.11	21:00	0
10:00	640.8	22:00	0
11:00	715.62	23:00	0
12:00	747.92	00:00	0

These measurements are from a pyranometer (its high-precision sensors that measure solar radiation on a planar surface) [38] fixed on a tilted surface at an angle of 45 degrees from the horizon, and these measurements are recorded every minute and averaged over an hour.

Figure (4.2) shows the hourly average solar radiation plotted from data of table (4.2):

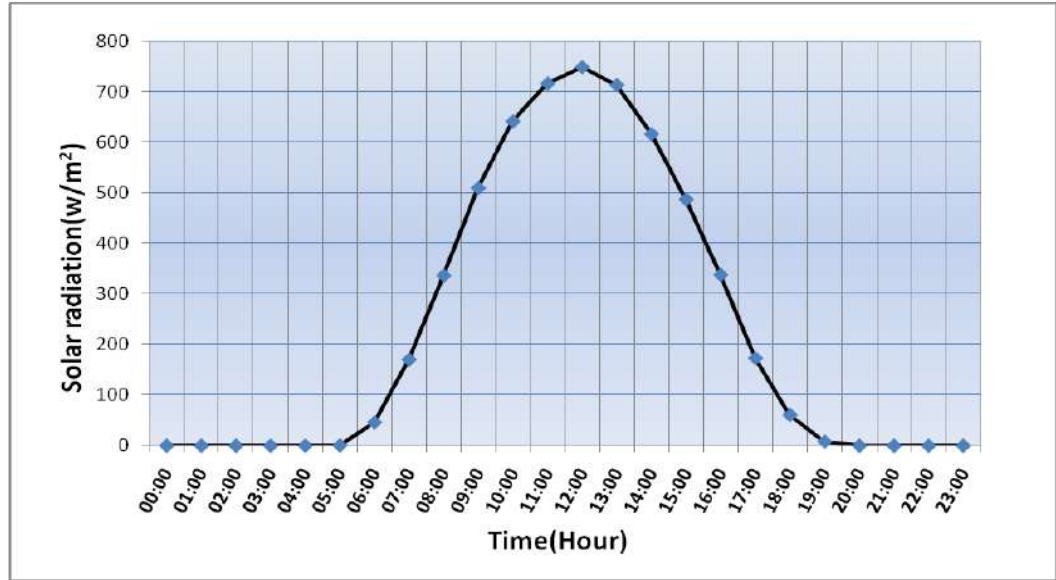


Figure (4.2): Hourly average solar radiation in Az Zubeidat village, on (20/7/2012).

From table (4.2) and figure (4.2), we show that we have enough potential for solar radiation in the interval period from 10 am to 2 pm, also we can obtain electric energy in morning and evening period because the solar radiation is more than 180 W/m [37].

4.2 Ambient Temperature in Palestine

Ambient temperature affects the PV generators efficiency, the relation between efficiency and PV cell temperature is inversed, figure (4.3) shows variation of efficiency with temperature at solar radiation of 1000W/m². There is a linear relation between PV cell temperature and the module efficiency. Decreasing temperature results in higher efficiency. So for a desired efficiency of a PV module we can determine what temperature of PV cell is needed, so by changing temperature around the PV module we can affect the efficiency. [39]

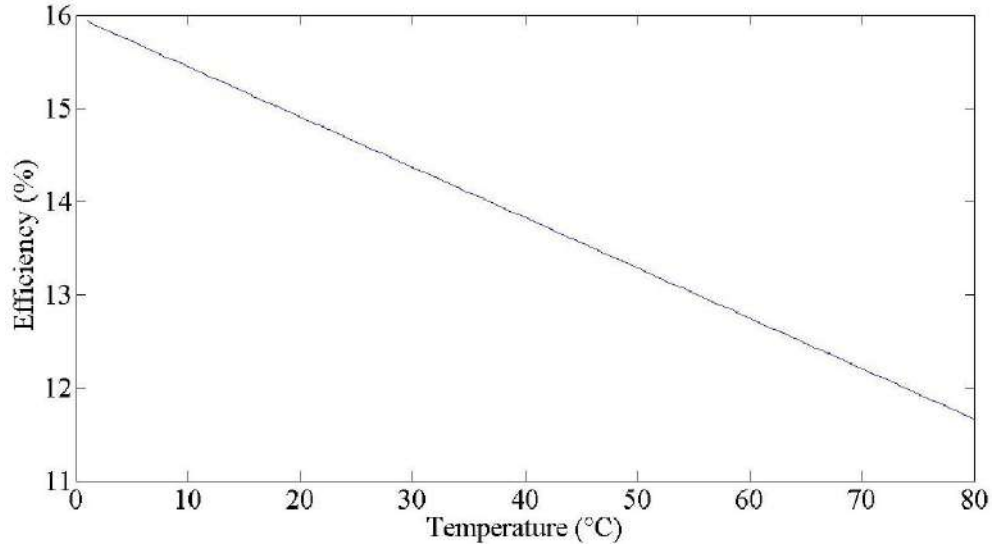


Figure (4.3): Variation of PV module efficiency with PV cell temperature [39].

Table (4.3) shows an example of the cell temperature and ambient temperature of Wadi Al- Maleh village in 20/7/2012, and these measurements are recorded every minute and averaged over an hour.

Table (4.3): The daily ambient and cell temperature for Wadi Al-Maleh village on 20-7-2012

Hours	Ambient temp.(°C)	Cell temp.(°C)	Hours	Ambient temp.(°C)	Cell temp.(°C)
01:00	35.39	30.82	13:00	40.70	62.89
02:00	34.77	30.31	14:00	41.45	58.37
03:00	34.25	29.84	15:00	42.13	53.91
04:00	33.76	29.39	16:00	42.52	46.80
05:00	33.48	29.27	17:00	41.47	40.85
06:00	33.28	30.00	18:00	39.84	37.42
07:00	33.98	33.77	19:00	38.83	34.57
08:00	35.43	39.17	20:00	37.21	32.54
09:00	36.58	47.74	21:00	36.27	31.44
10:00	37.71	55.52	22:00	35.43	30.82
11:00	38.84	60.45	23:00	34.71	30.13
12:00	39.76	63.02	00:00	35.97	31.59

Figure (4.4) shows the daily curve of the cell temperature and ambient temperature drawn from the data table (4.3). It shows that the maximum

cell temperature occurs around noon time (63°C), and the minimum cell temperature occurs in the early morning (29°C), and the maximum ambient temperature occurs a little after noon time (42.13°C), and the minimum ambient temperature occurs in the morning (33.28°C), also the figure shows that before 7:00 am and after 5:00 pm the ambient temperature is greater than cell temperature, in this time the PV cell radiate heat to the atmosphere so the temperature of it is less than ambient temperature, and the solar radiation has seemed to fade, and it's not enough to run the cells. (From figure(5.9) the minimum solar radiation necessary to run the PV cell effectively is 180 W/m^2).

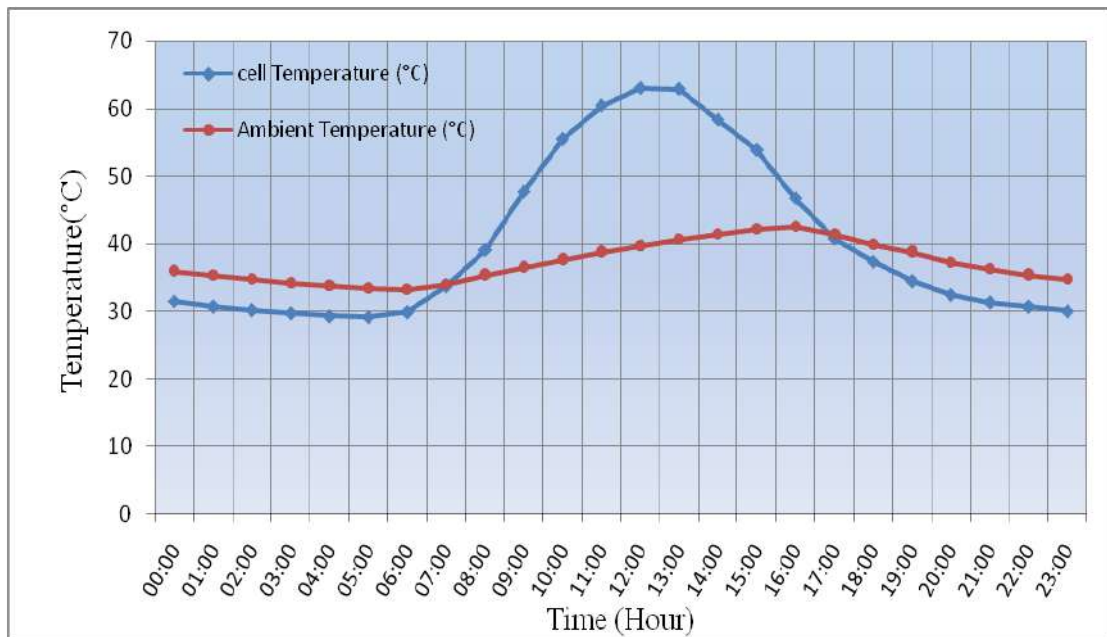


Figure (4.4): The daily ambient and cell temperature curves for Wadi Al- Maleh village on 20-7-2012.

Chapter Five

Photovoltaic Cell Technology

Introduction

Every day, the sun delivers energy to the earth free of charge. People can use this free energy thanks to a technology called photovoltaic's (PV), which converts the sun's energy into electricity.

The term photo comes from the Greek phos, which means "light." The term volt is a measure of electricity refers to Alessandro Volta (1745- 1827), a pioneer in the development of electricity. PV literally means light–electricity. [40]

The history of PV goes back to the year 1839, when Becquerel discovered the PV effect [41].

Bell laboratories produced the first solar cell in 1954, the efficiency of this cell was about 5%, and the cost was not a major issue, because the first cells were designed for space applications [41].

In the following years solar cell cost have decreased significantly as shown in figure (5.1).

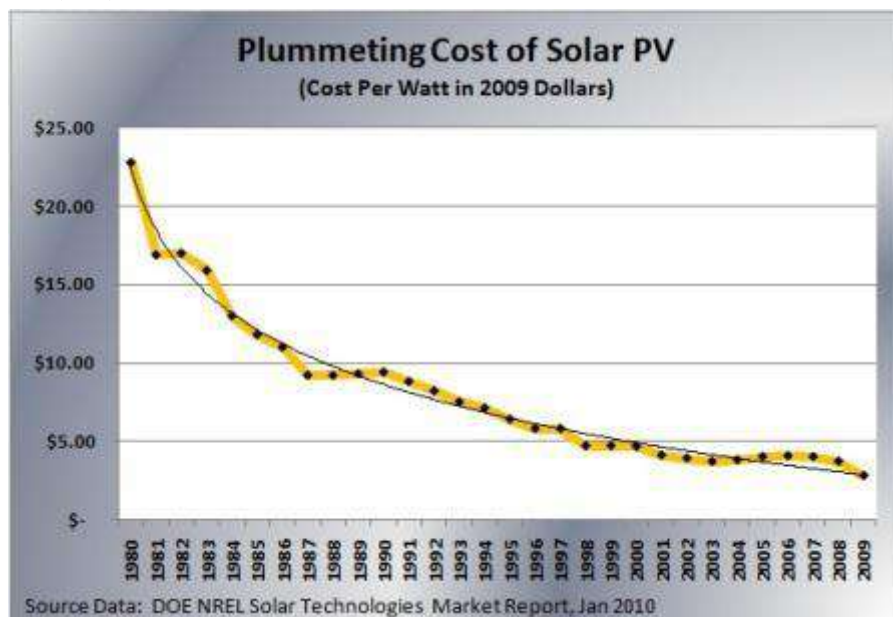


Figure (5.1): Increases in PV module efficiency, and decrease in cost per peak watt, 1978–1992.

PV offers the highest versatility among renewable energy technologies, one advantage is the modularity. All desired generator sizes can be realized from milliwatt range for the supply of pocket calculator to megawatt range for the public electricity supply [41]. PV module production increased since 1985 as shown in figure (5.2).

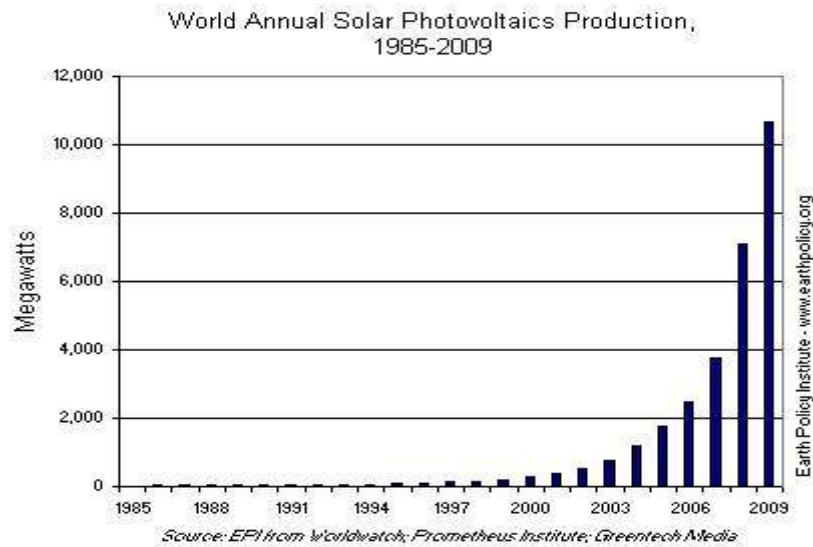


Figure (5.2): PV module production since 1985.

The growth of PV capacity in recent years around the world is shown in figure (5.3):

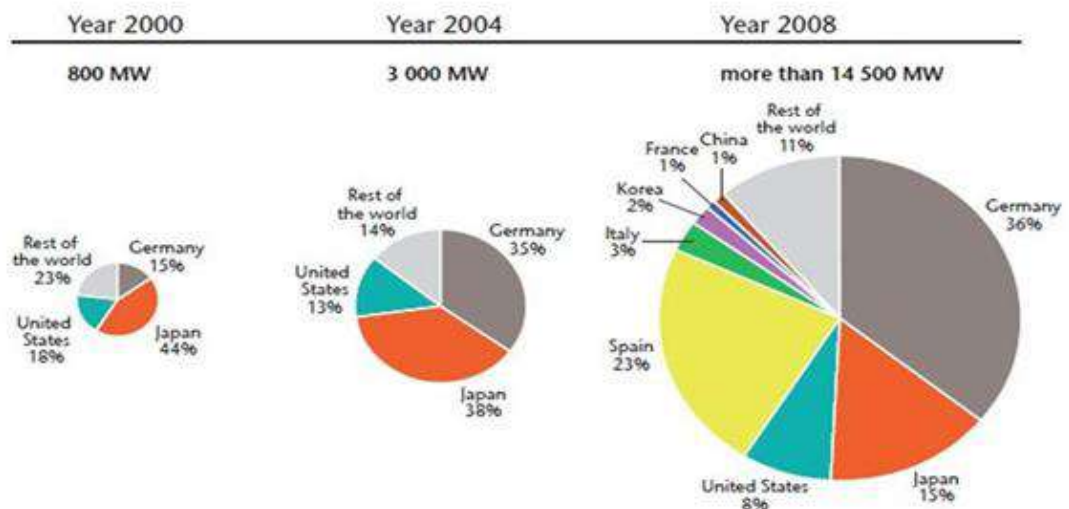


Figure (5.3): Growth of PV capacity in recent years around the world.

5.1 PV operating principle

Sunlight is composed of photons, or particles of radiant solar energy. These photons contain various amounts of energy depending on the wavelength of the solar spectrum. When the photons strike a solar cell some are absorbed while others are reflected. When the material absorbs sufficient photon energy, electrons within the solar cell material dislodge from their atoms. The electrons migrate to the front surface of the solar cell, which is manufactured to be more receptive to the free electrons. When many electrons, each carrying a negative charge, travel toward the front surface of the cell, the resulting imbalance of charge between the cell's front and back surfaces creates a voltage potential like the negative and positive terminals of a battery. When the two surfaces are connected through an external load, electricity flows [42].

Figure (5.4) shows the main components of PV cell and how it works [38].

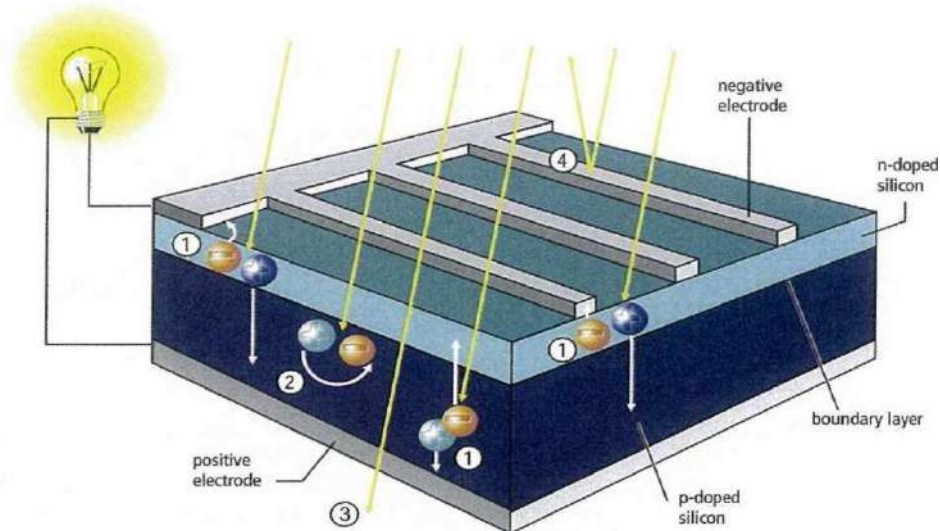


Figure (5.4): Design and functioning of a crystalline silicon solar cell.

Notes:

1. Charge separation;
2. Recombination;
3. Unused photon energy (e.g. transmission);
4. Reflection and shading caused by front contacts.

Losses occur at the solar cell due to recombination, reflection and shading caused by the front contacts. In addition, a large component of the long and short wavelength radiation energy cannot be used. As an example of this, the transmission losses (number 3 in the previous figure). A further portion of the unused energy is absorbed and converted into heat. Using the example of a crystalline silicon solar cell, the individual loss components are shown in the following energy balance sheet.

Energy balance of a crystalline solar cell:

100 per cent irradiated solar energy;

- 3 per cent reflection and shading caused by front contacts;
 - 23 per cent too low photon energy in long wavelength radiation.
 - 32 per cent too high photon energy in short wavelength radiation.
 - 8.5 per cent recombination losses;
 - 20 per cent potential difference in the cell, particularly in the space charge region.
 - 0.5 per cent series resistance (ohmic losses);
- = 13 per cent utilizable electrical energy [38].

5.2 PV Cell Types

There are many types of PV cells as shown in figure (5.5):

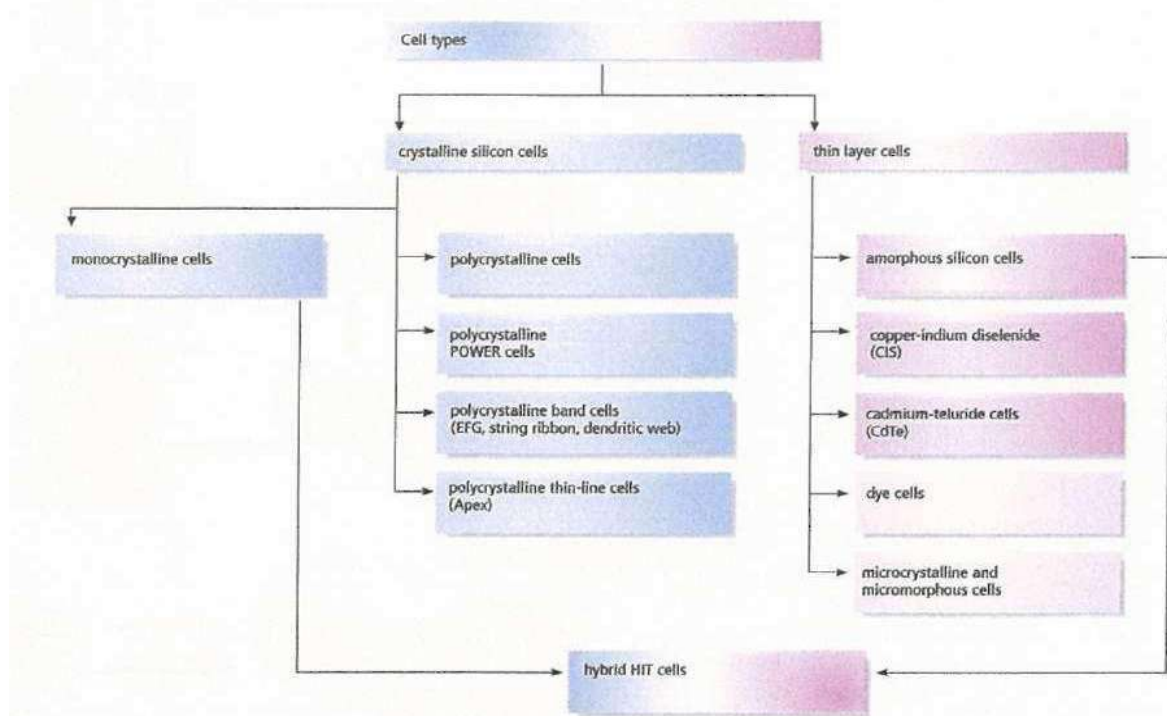


Figure (5.5): PV cell types [38].

The main characteristics of different commercially available PV cell types are:

- Mono-crystalline silicon
 - Open circuit Voltage (0.6-0.62).
 - Short circuit current (3.4A/100cm²).
 - Efficiency (10-15) %.
 - Most expensive to produce and buy.
 - Have very slow degradation (typically 0.25-0.5% per year).
 - Usually provide best warranties typically 25 years, with best over 90% power generation output for 10 years and 80% output to 20 years.

Output efficiency decreases by approximately 0.5% per degree C above the standard test temperature of 25°C [37].

➤ Poly-crystalline silicon

- Open circuit Voltage (0.55-0.58).
- Short circuit current (2.6-3.1A/100cm²)
- Efficiency (8-13) %.
- Moderately expensive to produce and buy.
- Output efficiency decreases by approximately 0.5% per degree C above the standard test temperature of 25°C [37].

➤ Amorphous silicon (non-crystalline, “thin film”)

- Open circuit Voltage (0.65-0.78).
- Short circuit current (1-2 A/100cm²)
- Efficiency (4.5-8) %.
- Least expensive to produce and buy.
- Efficiency degradation with time up to 30% of the initial efficiency after one year of operation.
- Output efficiency decreases slightly less than crystalline panels above the standard test temperature of 25°C [37].

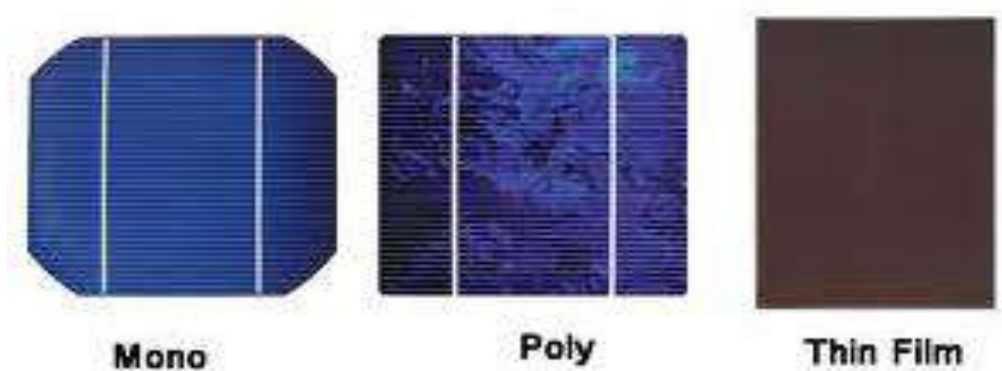


Figure (5.6): Different types of PV cells.

The PV cell is the basic building block of a PV system. Individual cells can vary in size from about 1 centimeter to about 10 centimeter across. However, one cell only produces 1 or 2 watts, which isn't enough power for most applications. To increase power output, cells are electrically connected to form module. Modules can be further connected to form an array as illustrated in figure (5.7). The term array refers to the entire generating plant, whether it is made up of one or several thousand modules. The number of modules connected together in an array depends on the amount of power output needed.

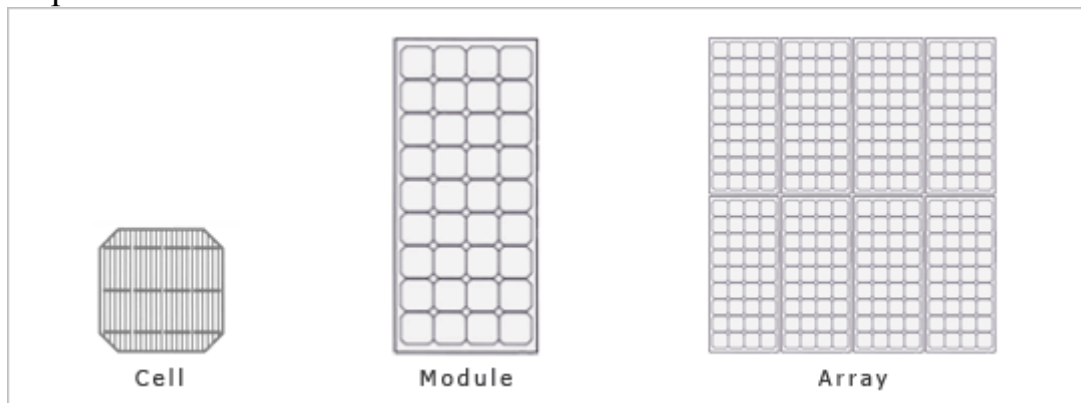


Figure (5.7): Cell, Module and Array.

5.3 Current/Voltage (I-V) Curve for PV Cell and Standard Test Condition (STC)

5.3.1 (I-V) Curve for PV cell

PV cells have current voltage relationship which is represented in I-V curve as shown in figure (5.8):

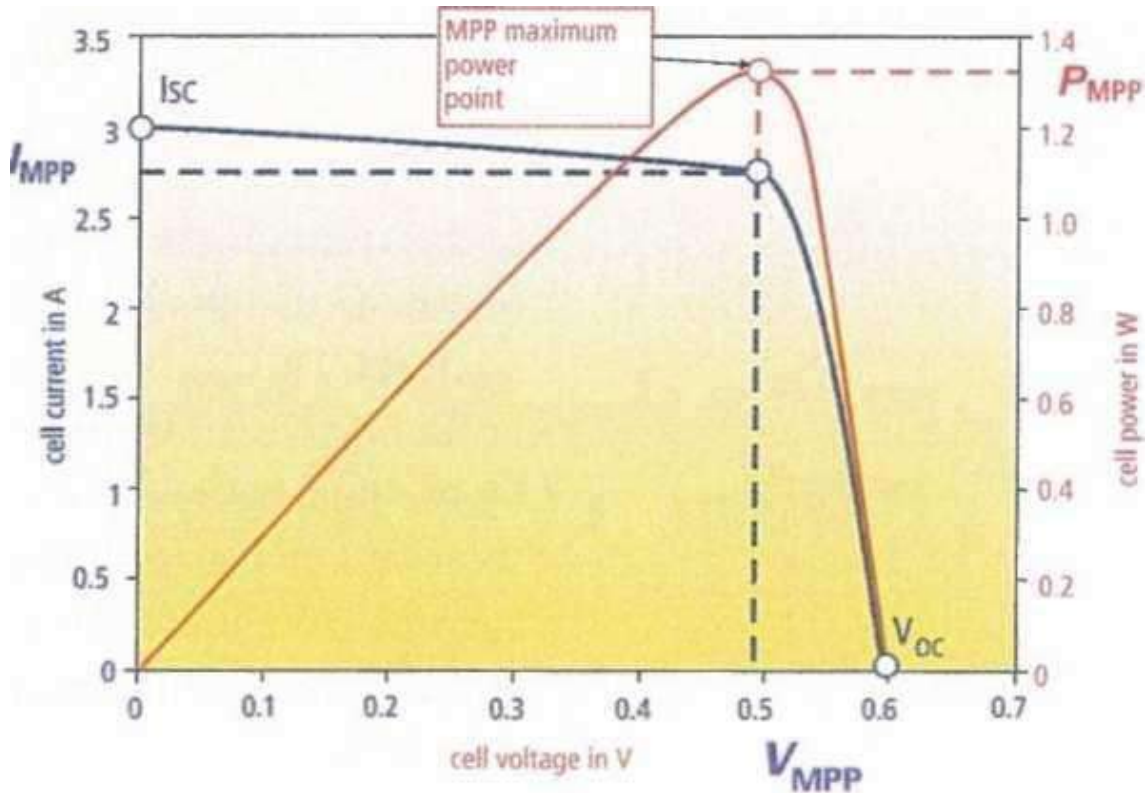


Figure (5.8): (I-V) Characteristics of a typical silicon PV cell (100cm^2) under standard test conditions [38].

Basically, the I-V curve is characterized by the following three points:

- The maximum power point (MPP) value is the point on the I-V curve at which the solar cell works with maximum power. For this point, the power P_{MPP} , the current I_{MPP} and voltage V_{MPP} are specified. This MPP power is given in units of peak watts (W_p).
- The short circuit current I_{sc} is approximately 5 per cent to 15 per cent higher than the MPP current. With crystalline standard cells ($10\text{cm} \times 10\text{cm}$) under STC, the short circuit current I_{sc} is around the 3A mark.
- The open circuit voltage V_{oc} registers, with crystalline cells, approximately 0.5V to 0.6V, and for amorphous cells is approximately 0.6V to 0.9V. [38]

5.3.2 Standard test conditions (STC)

In order to be able to compare different cells or, indeed, PV modules with one another, uniform conditions are specified for determining the electrical data with which the solar cell characteristic I-V curve is then calculated. These STC as they are known, relate to the IEC 60904/DIN EN 60904 standards:

- 1 Vertical irradiance E of 1000 W/m^2 ;
- 2 Cell temperature T of 25°C with a tolerance of $\pm 2^\circ\text{C}$;
- 3 Defined light spectrum (spectral distribution of the solar reference irradiance according to IEC 60904-3) with an air mass $AM = 1.5$.

5.4 Effect of Solar Radiation and Temperature on PV Performance

5.4.1 Effect of solar radiation on PV performance

Figure (5.9) shows the Open circuit voltage V_{OC} and short circuit current I_{SC} depending upon irradiance:

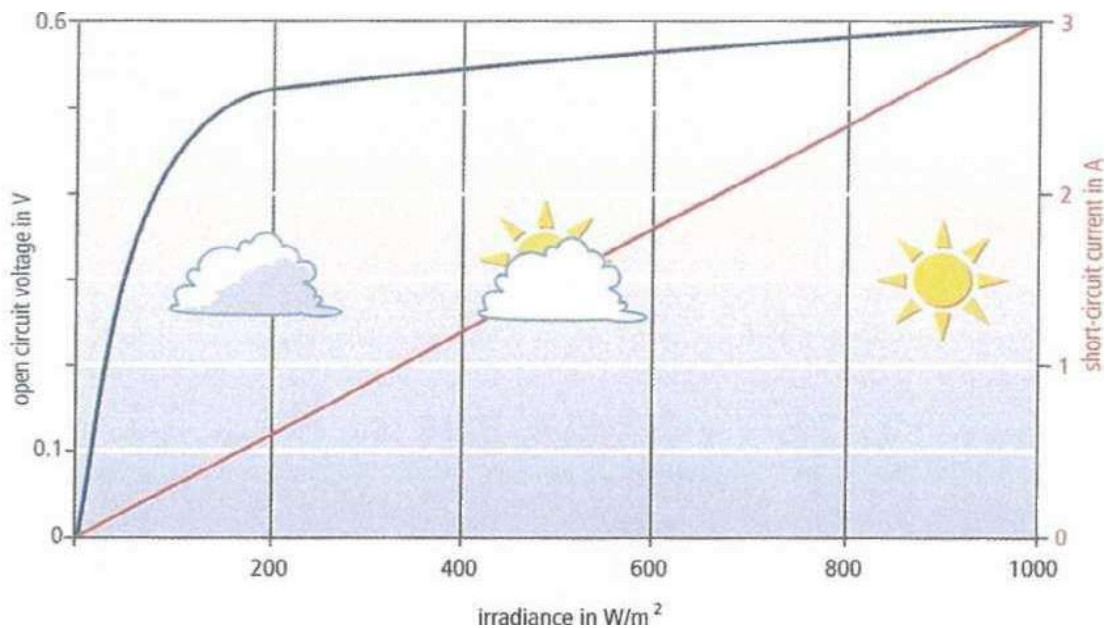


Figure (5.9): V_{OC} and I_{SC} depending upon irradiance [38].

The irradiance will affect the current generated by a solar cell, the higher the irradiance the higher the current. The effect of irradiance on voltage is minimal. The change in Irradiance can be calculated, the manufacturer's standards will provide the user with a short circuit current, which can be recalculated for the new irradiance value by equation (5.1)

$$I_{sc}(G) = (I_{sc} \text{ rated@}1000 \text{ W/m}^2) \times (G/G_{stc}) \quad (5.1)$$

Where

I_{sc} : Short circuit current.

G: The actual radiation.

G_{stc} : STC value of radiation (1000 W/m^2).

Figure (5.10) shows the effect of radiation variation at I-V module curve consisting of 36 cells of mono crystalline silicon [Siemens, SR50] at constant temperature, and figure (5.11) shows the effect of radiation variation at P-V curve for the same module.[41]

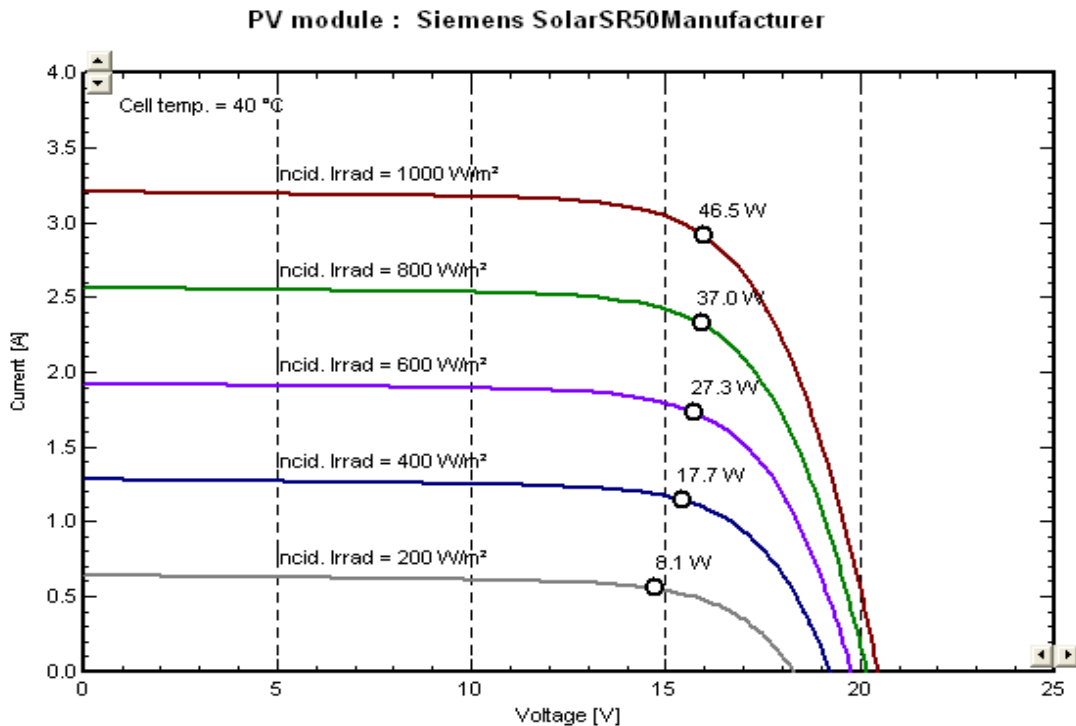


Figure (5.10): PV module (I-V) curve with variation of solar radiation and constant temperature [41].

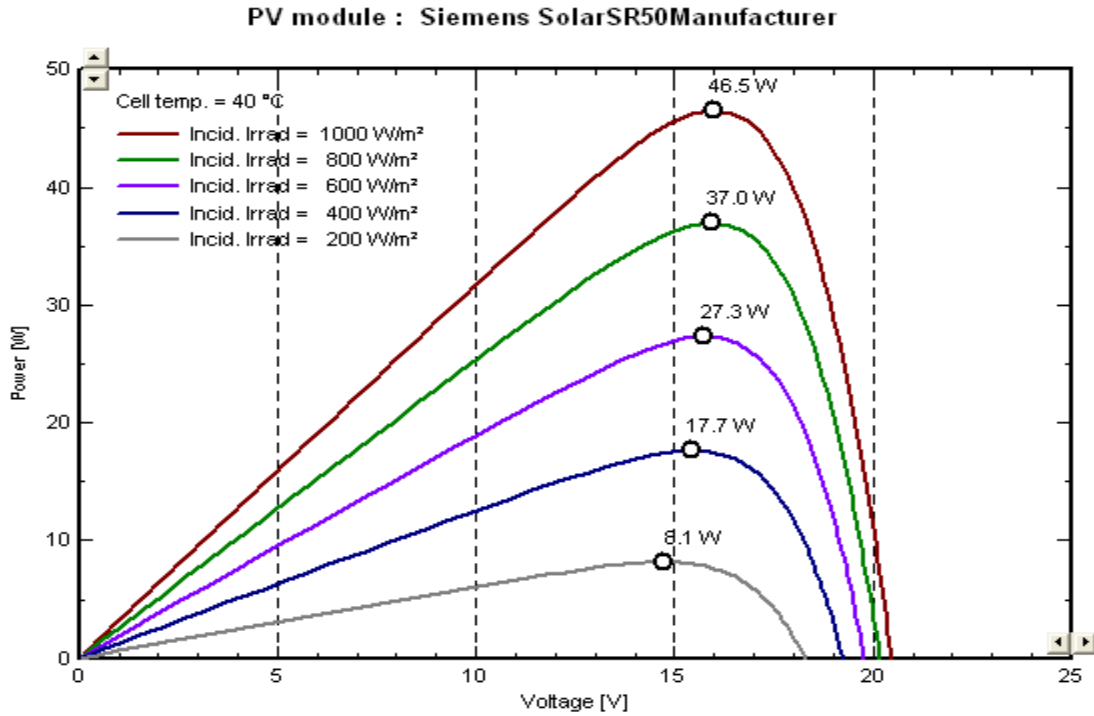


Figure (5.11): PV module (P-V) curve with variation of solar radiation and constant temperature [41].

5.4.2 Effect of cell temperature on PV performance

Solar cells vary under temperature changes; the change in temperature will affect the power output from the cells. The voltage is highly dependent on the temperature and an increase in temperature will decrease the voltage.

Each solar module will have manufacturing standards; the normal operating cell temperature (NOCT) should be among these standards. The NOCT is the temperature cells will reach when operated at open circuit in an ambient temperature of 20°C at AM 1.5 irradiance conditions, $G = 0.8 \text{ kW/m}^2$ and a wind speed less than 1 m/s . For variations in ambient temperature and irradiance the cell temperature (in $^\circ\text{C}$) can be estimated quite accurately with the linear approximation that

$$T_c = T_a + ((\text{NOCT} - 20)/0.8) \times G \quad (5.2)$$

The combined effects of irradiance and ambient temperature on cell performance merit careful consideration. Since the open circuit voltage of a silicon cell decreases by $2.3 \text{ mV}/^{\circ}\text{C}$, the open circuit voltage of a module will decrease by $2.3 \text{ mV}/^{\circ}\text{C}$, where n is the number of series cells in the module. Hence, for example, if a 36-cell module has a NOCT of 40°C with $V_{\text{OC}} = 19.40 \text{ V}$, when $G = 0.8 \text{ kW}/\text{m}^2$, then the cell temperature will rise to 55°C when the ambient temperature rises to 30°C and G increases to $1 \text{ kW}/\text{m}^2$. This 15°C increase in cell temperature will result in a decrease of the open circuit voltage to 18.16 V , a 6% decrease. Furthermore, excessive temperature elevation may cause the cell to fail prematurely [38].

Figure (5.12) shows the effect of cell temperature variation at PV module consisting of 36 cells of mono crystalline silicon [Siemens, SR50] at constant radiation.

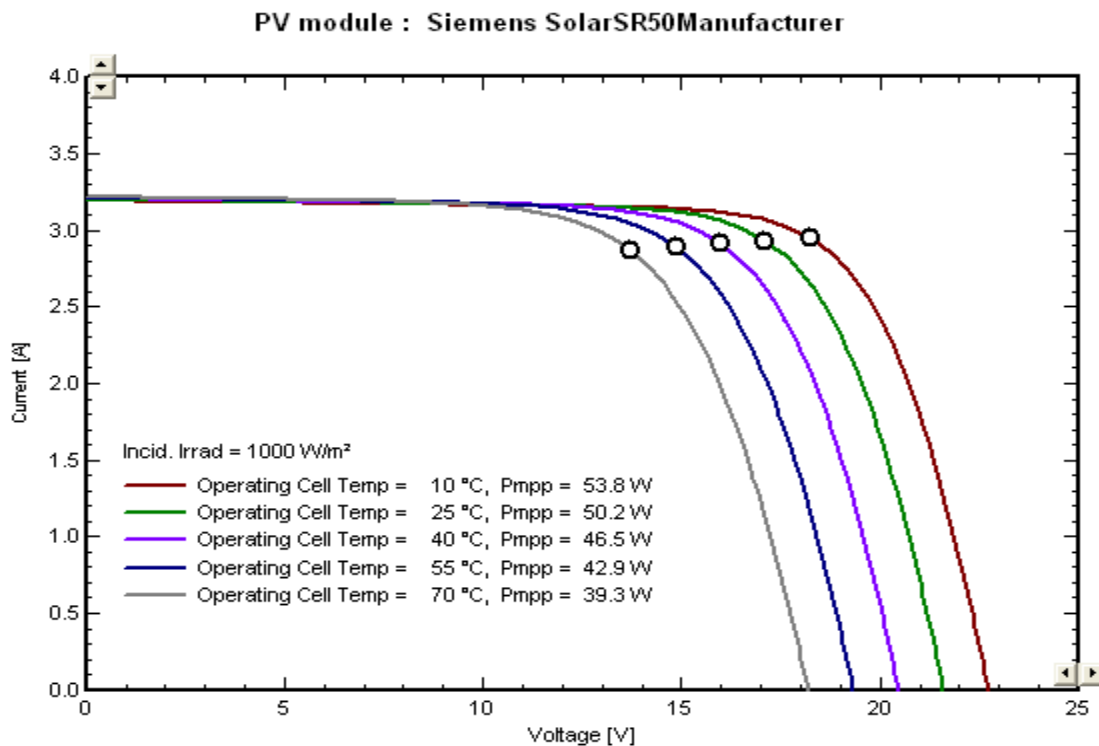


Figure (5.12): PV (I-V) curve with variation of cell temperature and constant radiation [41].

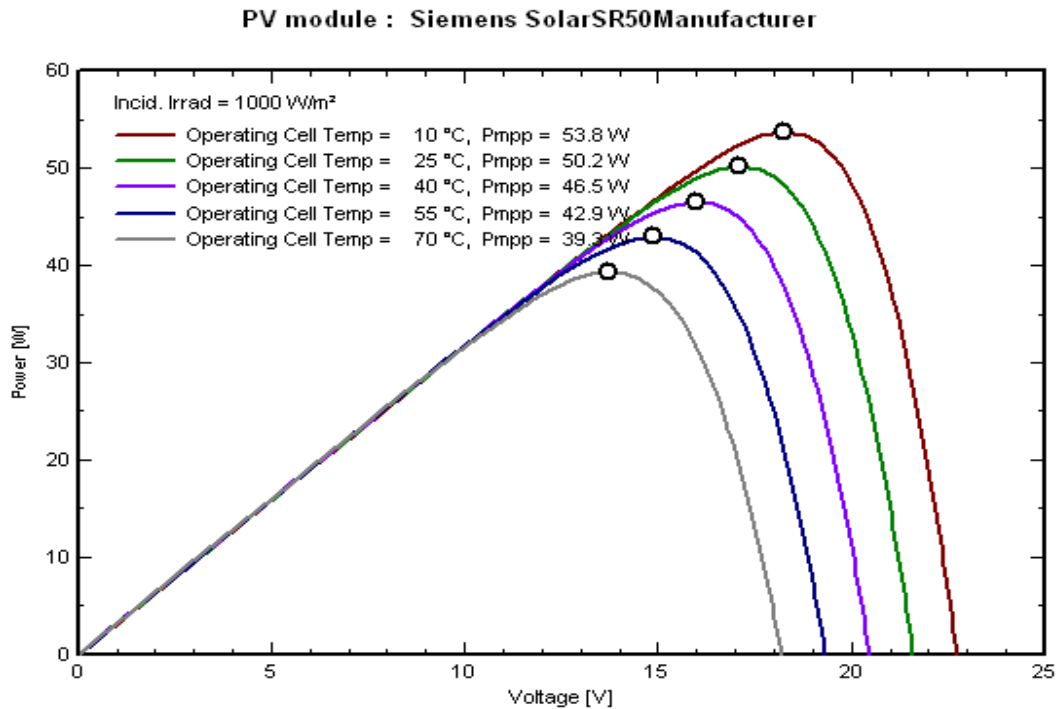


Figure (5.13): PV (P-V) Curve with variation of cell temperature and constant radiation [41].

5.5 Types of PV System:

There are two major types of PV system, and it depends on the connection of the system if it's connected to the main grid or it stands alone without any connection, these types are :

- Stand-alone systems.
- Grid-tied systems.

5.5.1 Stand-alone systems

These systems are most common in remote locations without utility grid service, stand-alone solar electric systems can work anywhere. These systems operate independently from the grid to provide loads with electricity, and there are many types of this system.

Types of stand-alone systems:

a. Stand-alone DC system without storage.

It's the simplest type, where the DC output of a PV module is directly connected to a DC load. The critical part of designing a well performing direct-coupled system is the matching of impedance of the electrical load to the maximum power output of the PV module. It can be used to operate pumping machine where water is pumped in the day to reservoir for using at night. Figure (5.14) shows the DC system without storage [35].

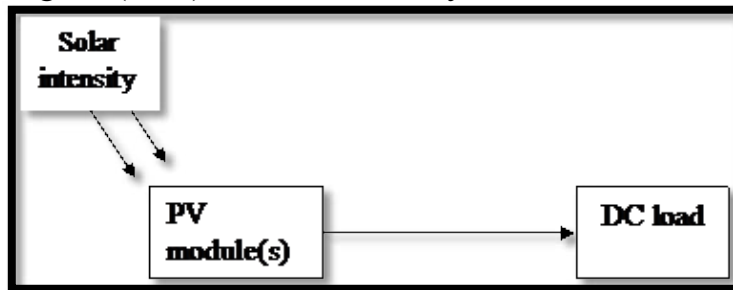


Figure (5.14): DC System without storage [35].

❖ The disadvantages for this type of stand-alone are:

- It can only be used in the day to supply load as there is no battery for storing energy.
- It cannot be used for AC load

b. Stand-alone AC system without storage.

This is another type of stand-alone system, it is the type that incorporate inverter unit for conversion of DC voltage to AC at appropriate voltage level [35].

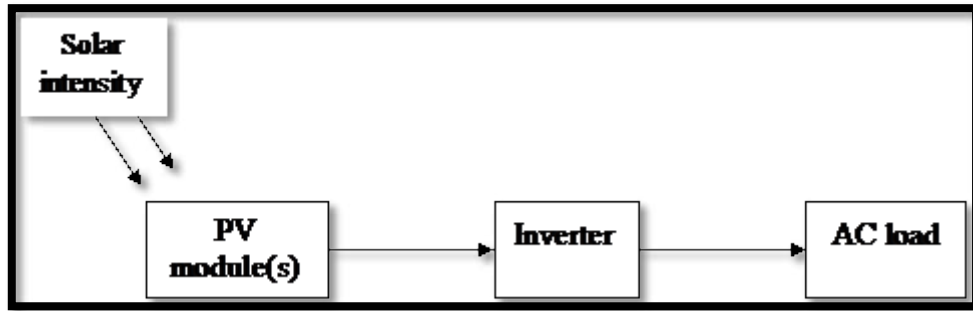


Figure (5.15): AC system without storage [35].

❖ The disadvantage of this system is

- The lack of storage unit, so it will not supply load at night.

c. Stand-alone system with DC output and battery.

Figure (5.16) shows the block diagram of a typical stand-alone PV system. A solar PV array, battery, and charge controller are the three primary components of the PV system. The solar array generates DC power for the load and charges the battery, which serves as the energy storage device that powers the load when there is no output from the array. The charge controller regulates the output of the PV array and ensures proper charging of the battery, thus protecting it from abuse [35].

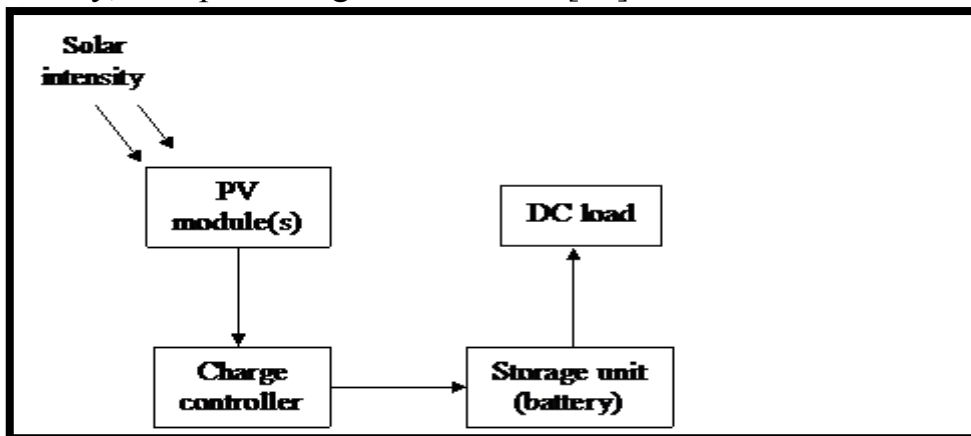


Figure (5.16): Stand-alone system with DC output and battery [35].

d. Stand-alone system with battery and DC and AC output.

Figure (5.17) shows the stand-alone system with battery for storage and both types of output loads DC and AC [35].

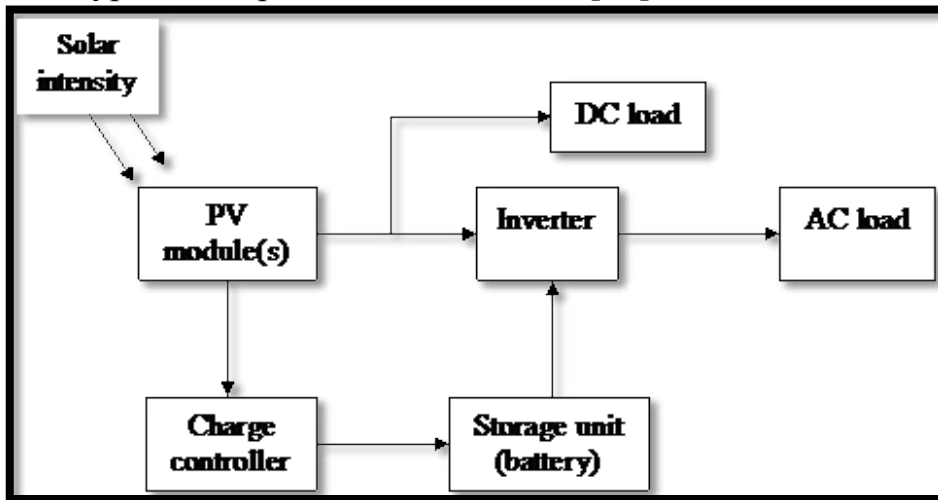


Figure (5.17): Stand-alone system with battery and DC and AC output [35].

e. Stand-alone system with battery and without DC output.

This system is only for AC loads and there is no DC loads. We can use it for one phase and three phases; it depends on the type of the inverter [35].

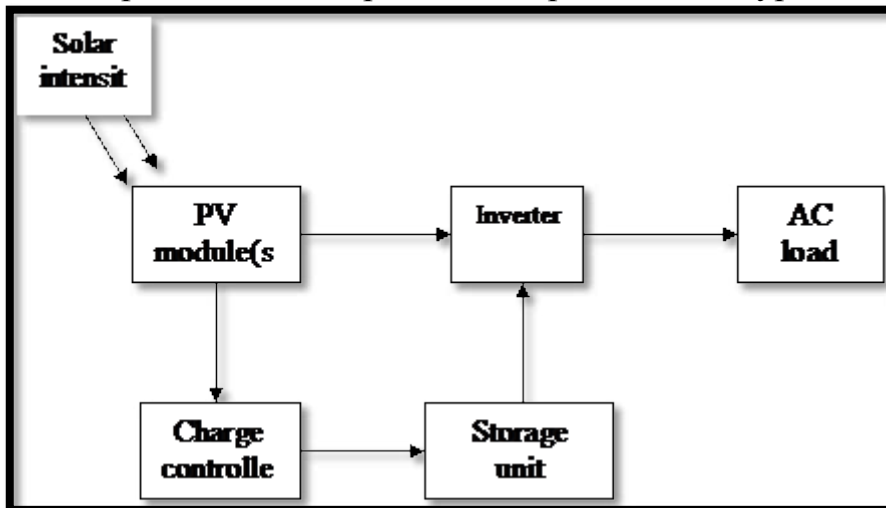


Figure (5.18): Stand-alone system with battery and without DC output [35].

f. Stand-alone system with engine generator as back-up (hybrid system) [35].

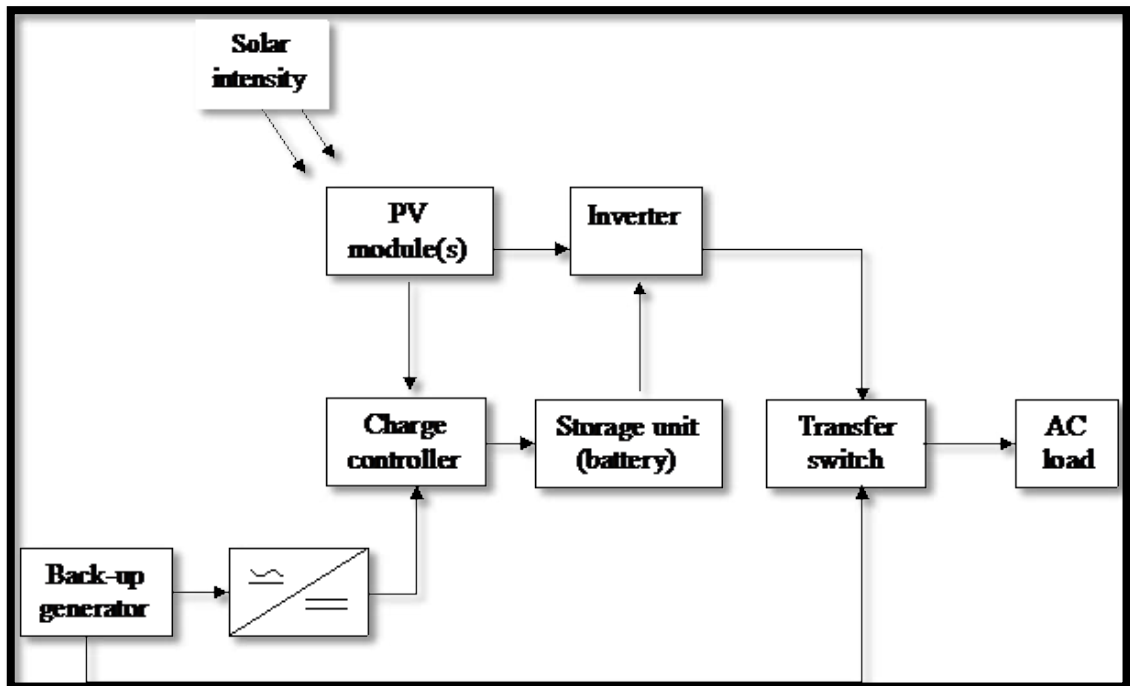


Figure (5.19): Stand-alone system with engine generator as back-up [34].

5.5.2 Grid-tied PV systems

Grid-tied systems are designed to operate in parallel with and interconnected with the electric utility grid. Below are the block diagrams of grid-tied systems.

a. Grid-tied system without battery [35].

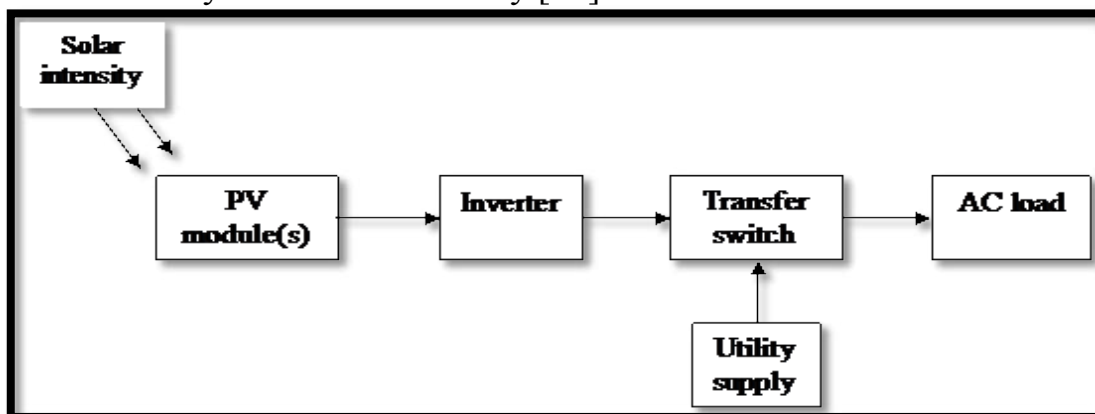


Figure (5.20): Grid-tied system with no battery [35].

b. Grid-tied system with batteries for storing charges [35].

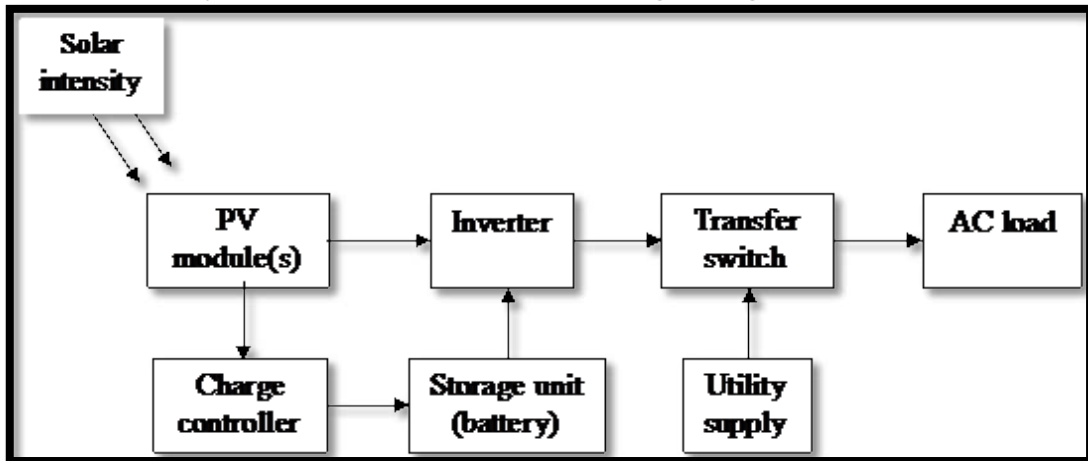


Figure (5.21): Grid-tied system with batteries for storing charges [35].

c. Grid-tied system with utility connected to charge battery [35].

Grid-tied system can also be connected in a way that utility supply will be charging battery in the period of low light intensity. It has the same features as stand-alone system with engine generator back-up. In the case of long cloudy days and utility outage, there is likely to be blackout.

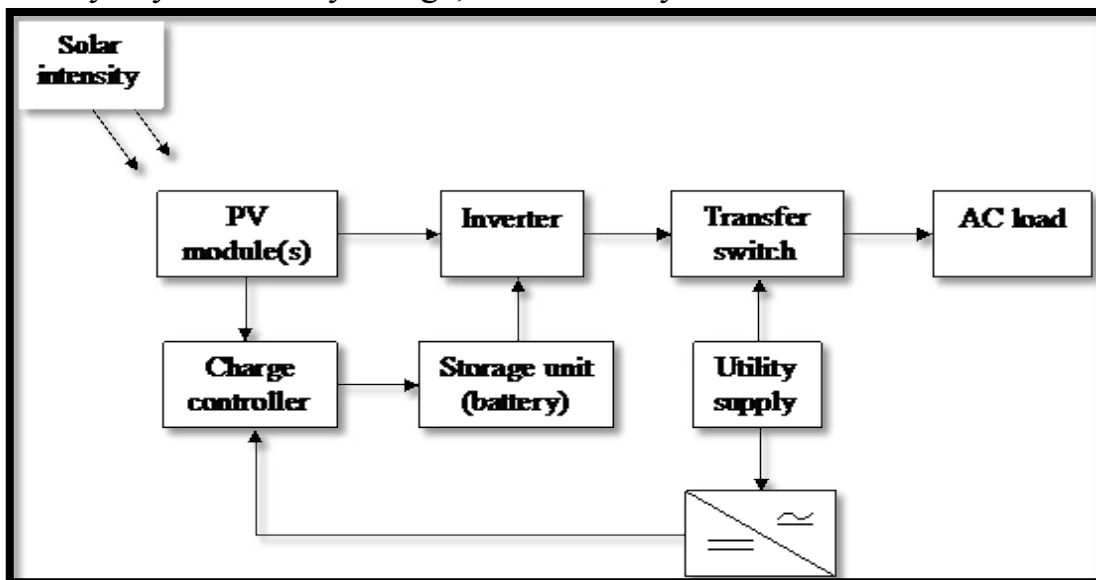


Figure (5.22): Grid-tied system with utility connected to charge battery [35].

Chapter Six

Case Study: Design of

Wadi Al- Maleh BW Desalination System by Using RO

Membrane Powered by PV System

6.1 About Wadi Al- Maleh Village.

6.1.1 Wadi Al- Maleh location and physical characteristics.

Wadi Al- Maleh is a Palestinian village in Jericho Governorate located (horizontally) 35.4km north of Jericho City. Wadi Al- Maleh is bordered by the Jordan River to the east, Marj Na'ja village to the north, Tubas city to the west, and Marj al Ghazal village to the south [43].

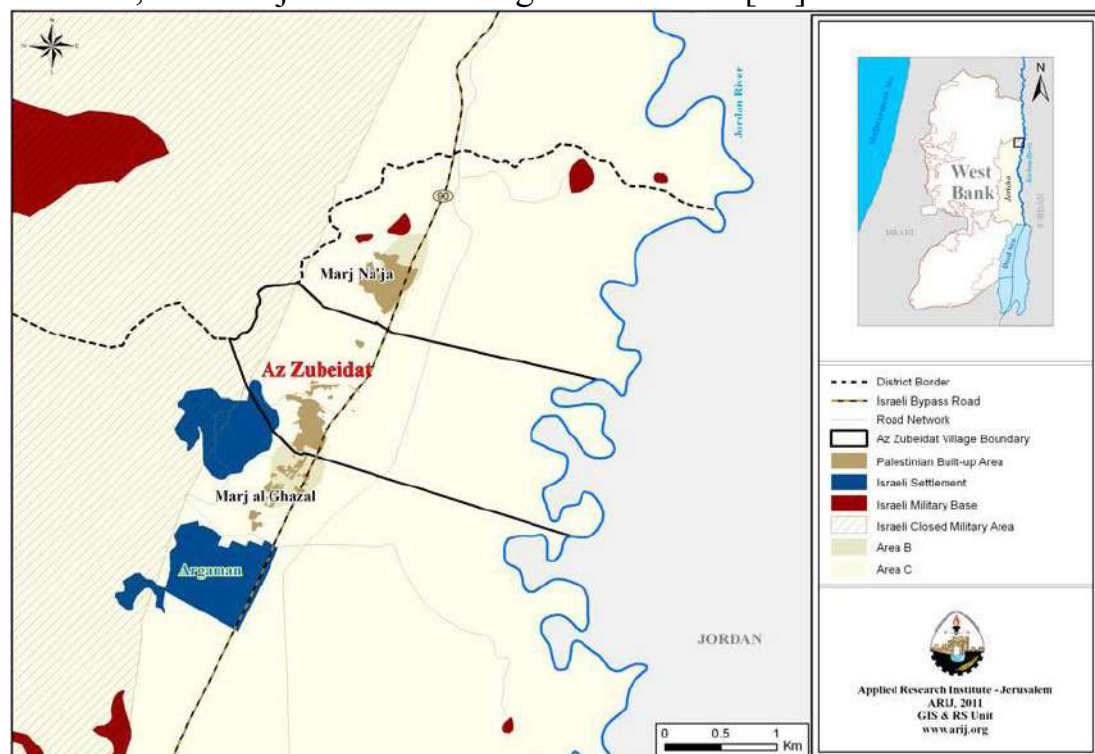


Figure (6.1): Wadi Al- Maleh location and borders map.

Wadi Al- Maleh is located at an altitude of 275m below sea level with a mean annual rainfall of 192mm. The average annual temperature is 23°C, and the average annual humidity is approximately 48% [43].

6.1.2 Population

According to the Palestinian Central Bureau of Statistics (PCBS), the total population of Wadi Al- Maleh in 2007 was 1,357 of whom 696 were male, and 661, female. There were additionally registered to be 199 households living in 199 housing units [43].

6.2 Design and Selection of the System Components for Wadi Al-Maleh Project

6.2.1 Design the system using ROSA program

Wadi Al- Maleh project is the first BWRO desalination system operated by solar electric power (PV) in West Bank- Palestine. This system was designed by using ROSA from DOW Chemicals Company.

Wadi Al- Maleh village has only three BW wells. The BW from one well is pumped to a cement storage tank, located at 45m higher than the level of the village, the capacity of the storage tank is about 200m³ and its water is directly used to feed RO desalination system.

Steps used to design the system by ROSA program:

a. Project Information

The first step is fill the project information in ROSA program, like project name, units of temperature, pressure...etc, as shown in figure (6.2).

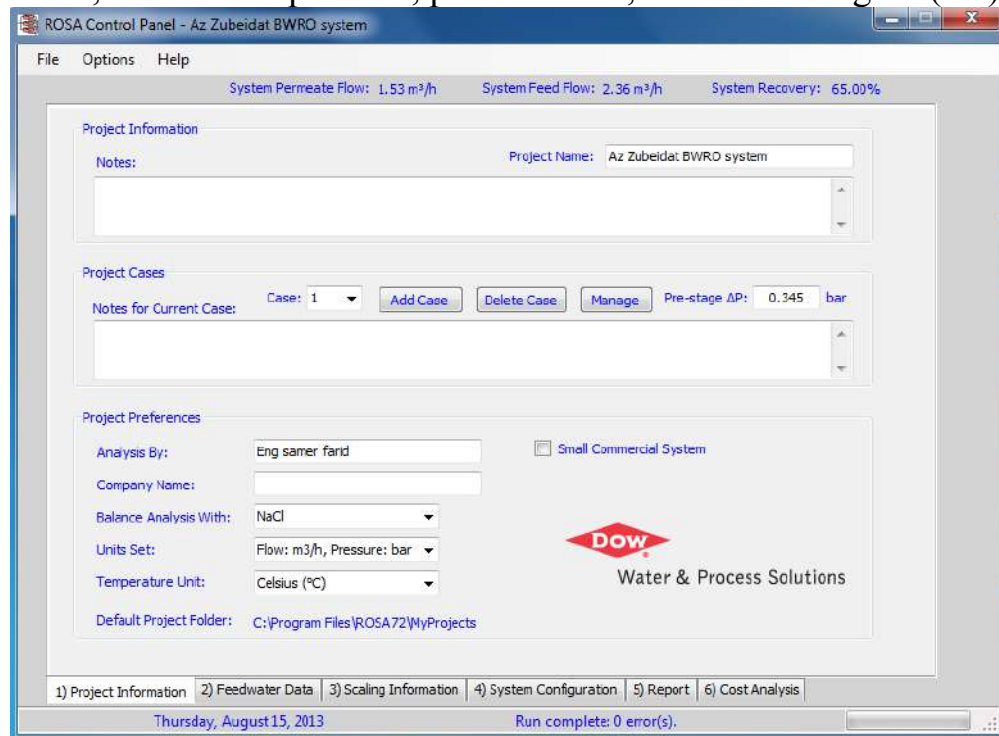


Figure (6.2): Project information at ROSA program.

b. Feed water Data

The second step is fill feed water type and composition as in table (1.4), as seen in figure (6.3).

ROSA Control Panel - Az Zubeidat BWRO system

File Options Help

System Permeate Flow: 1.53 m³/h System Feed Flow: 2.36 m³/h System Recovery: 65.00%

Water Type: Well Water SDI < 3 Open Water Profile Library

Feed Percentage: 100.0 (%) Feed Number: 1 Feed Streams: 1

Ions	mg/l	ppm CaCO ₃	meq/l	Total Conc.(mg/l)
Ammonium (NH ₄)	0	0.000	0.000	0.00
Potassium (K)	13.1	16.751	0.335	13.10
Sodium (Na)	483	1050.457	21.009	483.00
Magnesium (Mg)	146	600.527	12.011	146.00
Calcium (Ca)	200	499.002	9.980	200.00
Strontium (Sr)	0	0.000	0.000	0.00
Barium (Ba)	0	0.000	0.000	0.00
Carbonate (CO ₃)	1.819	3.031	0.061	1.82
Bicarbonate (HCO ₃)	305	249.980	5.000	305.00
Nitrate (NO ₃)	36	29.030	0.581	36.00
Chloride (Cl)	1200	1692.381	33.848	1200.00
Fluoride (F)	0	0.000	0.000	0.00
Sulfate (SO ₄)	184.566	192.256	3.845	184.57
Silica (SiO ₂)	21.6	n.a.	n.a.	21.60
Boron (B)	0.46	n.a.	n.a.	n.a.

☒ Specify Individual Solutes

Total Dissolved Solids: 2593.7 mg/l

Feed Parameters

Temperature: 25.0 °C

Flow Rate: 2.36 m³/h

pH: 7.6

Charge Balance

Cations: 43.33 Add Sodium

Anions: 43.34 Add Calcium

Balance: 0.00 Adjust Cations

Adjust Anions

Adjust All Ions

System Temp: 25.0 °C System pH: 7.60 Save Water Profile to Library

Note: Any changes in raw feedwater composition will affect scaling calculations. Please review scaling calculations.

1) Project Information 2) Feedwater Data 3) Scaling Information 4) System Configuration 5) Report 6) Cost Analysis

Thursday, August 15, 2013 Run complete: 0 error(s).

Figure (6.3): Feed water Data at ROSA program.

c. Scaling information

Third step is filling dosing chemical if it is used in this system as shown in figure (6.4)

ROSA Control Panel - Az Zubeidat BWRO system

File Options Help

System Permeate Flow: 1.53 m³/h System Feed Flow: 2.36 m³/h System Recovery: 65.00%

Scaling Calculations Options

☐ No chemicals added

☒ User-adjusted pH

☐ Ion-exchange softening

Antiscalants are required. Consult your antiscalant manufacturer for dosing and maximum allowable system recovery.

	Feed	Adj. Feed	Concentrate
pH	7.6	7.6	8.06
LSI	0.742	0.742	2.087
Stiff & Davis Index	0.725	0.725	1.670
TDS (mg/l)	2,594	2,594	7,411
Ionic Strength (molal)	0.056	0.056	0.162
HCO ₃ (mg/l)	305.000	305.000	871.429
CO ₂ (mg/l)	7.830	7.830	7.830
CO ₃ (mg/l)	1.819	1.819	5.197
CaSO ₄ (% Saturation)	4.73	4.73	18.39
BaSO ₄ (% Saturation)	0.0	0.0	0.0
SrSO ₄ (% Saturation)	0.0	0.0	0.0
CaF ₂ (% Saturation)	0.0	0.0	0.0
SiO ₂ (% Saturation)	17.28	17.28	43.66
Mg(OH) ₂ (% Saturation)	0.0079	0.0079	0.18

Ion-exchange Leakage

Ca Leakage: 0.1 (mg/L)

Mg Leakage: 0 (mg/L)

Recovery and Temperature

Recovery: 55.00 (%)

Temperature: 25.0 °C

☐ Use original feed

☒ Use adjusted feed

User-adjusted pH

Dosing Chemical: H₂SO₄

pH: 7.6 GO

Concentrate LSI: 2.087 GO

1) Project Information 2) Feedwater Data 3) Scaling Information 4) System Configuration 5) Report 6) Cost Analysis

Thursday, August 15, 2013 Run complete: 0 error(s).

Figure (6.4): Scaling information at ROSA program.

d. System Configuration:

In this step calculate feed flow, recovery, permeate flow, and determine type of membrane, number of membranes, number of pressure vessels in each stage, number of elements in each vessel, the type of membrane used and many thing else, as shown in figure (6.5)

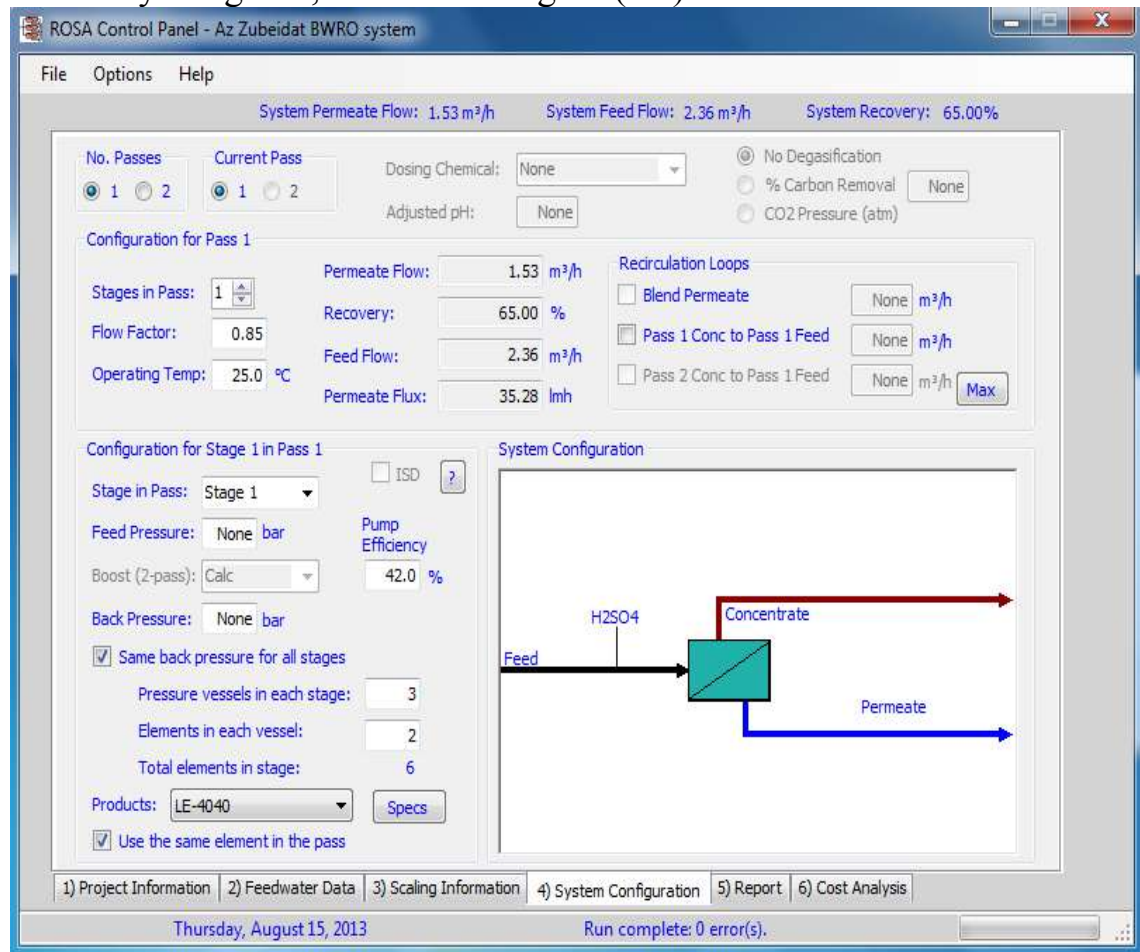


Figure (6.5): System configuration at ROSA program.

e. Report

When press on report the program is running and give the following report:

Project Information: System Details

Feed Flow to Stage 1	2.36 m ³ /h	*Pass 1 Permeate Flow	1.53 m ³ /h	Osmotic Pressure:	
Raw Water Flow to System	2.36 m ³ /h	Pass 1 Recovery	65.00 %	Feed	1.66 bar
*Feed Pressure	10.73 bar	Feed Temperature	25.0 C	Concentrate	4.49 bar
Flow Factor	0.85	Feed TDS	2593.73 mg/L	Average	3.07 bar
Chem Dose (100% H ₂ SO ₄)	0.00 mg/L	Number of Elements	6	Average NDP	7.35 bar
Total Active Area	43.48 M ²	Average Pass 1 Flux	35.28 lmh	Power	1.68 kW
Water Classification: Well Water SDI < 3				Specific Energy	1.09 kWh/m ³

Stage	Element	#PV	#Ele	Feed Flow (m ³ /h)	Feed Press (bar)	Recirc Flow (m ³ /h)	Conc Flow (m ³ /h)	Conc Press (bar)	Perm Flow (m ³ /h)	Avg Perm Flux (lmh)	Perm Press (bar)	Boost Press (bar)	Perm TDS (mg/L)
1	LE-4040	3	2	2.36	10.40	0.00	0.83	10.35	1.53	35.28	0.00	0.00	77.33

Pass Streams (mg/L as Ion)					
Name	Feed	Adjusted Feed	Concentrate Stage 1	Permeate Stage 1	Total
NH ₄	0.00	0.00	0.00	0.00	0.00
K	13.10	13.10	32.81	2.48	2.48
Na	483.00	483.01	1351.31	15.46	15.46
Mg	146.00	146.00	411.89	2.83	2.83
Ca	200.00	200.00	564.72	3.61	3.61
Sr	0.00	0.00	0.00	0.00	0.00
Ba	0.00	0.00	0.00	0.00	0.00
CO ₃	1.82	1.82	12.84	0.00	0.00
HCO ₃	305.00	305.00	835.48	11.06	11.06
NO ₃	36.00	36.00	83.51	10.42	10.42
Cl	1200.00	1200.00	3379.16	26.61	26.61
F	0.00	0.00	0.00	0.00	0.00
SO ₄	184.57	184.57	522.91	2.38	2.38
SiO ₂	21.60	21.60	61.02	0.37	0.37
Boron	0.46	0.46	0.63	0.37	0.37
CO ₂	7.83	7.83	12.51	8.28	8.27
TDS	2593.72	2593.73	7259.30	77.33	77.33
pH	7.60	7.60	7.74	6.30	6.30

Stage Details

Stage	Element	Recovery	Perm Flow (m ³ /h)	Perm TDS (mg/L)	Feed Flow (m ³ /h)	Feed TDS (mg/L)	*Feed Press (bar)
1		0.38	0.30	51.16	0.79	2593.73	10.40
2		0.44	0.21	113.71	0.49	4137.53	10.37

Figure (6.6): The report resulting from ROSA software.

*Information that under its black line is the most interested in the design process.

If changes recovery and run ROSA software, changes occur in permeate TDS and feed pressure shown in table (6.1), TDS of feed water and number of elements is constant.

Table (6.1) Changing recovery and its effect on permeate TDS, and feed pressure.

% Recovery	Permeate TDS (mg/L)	Feed pressure (bar)
50	73.31	8.07
55	73.53	8.88
60	74.85	9.76
65	77.33	10.75
70	81.18	11.86
75	86.77	13.14
80	94.84	14.71

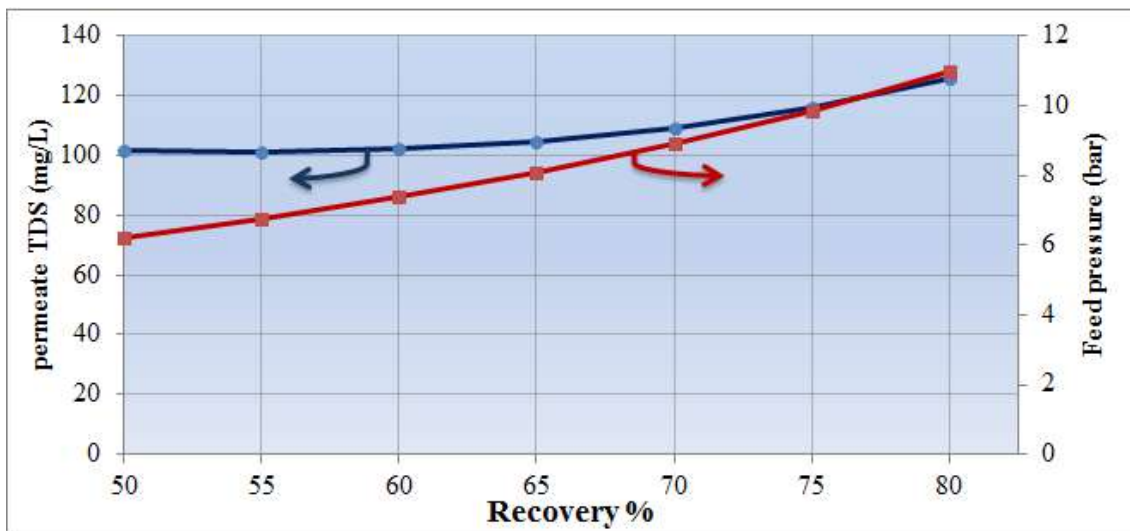


Figure (6.7): Curves of recovery versus permeate TDS, and feed pressure.

As shown in figure (6.7) when recovery is increased the Permeate TDS is increased and feed pressure is increased, then energy required to the project is increased.

Due to the limited available budget of the project, and limited available roof surface area for PV system (when energy is increased, required surface area for PV is increased), the option 65% recovery was selected , due to

lowest permeate salt content and the optimum feed pressure to avoid membrane deterioration [5].

6.2.2 Select the system components for Wadi Al- Maleh project

Figure (6.8) shows the schematic diagram for Wadi Al- Maleh project, and the main components that compose the project.

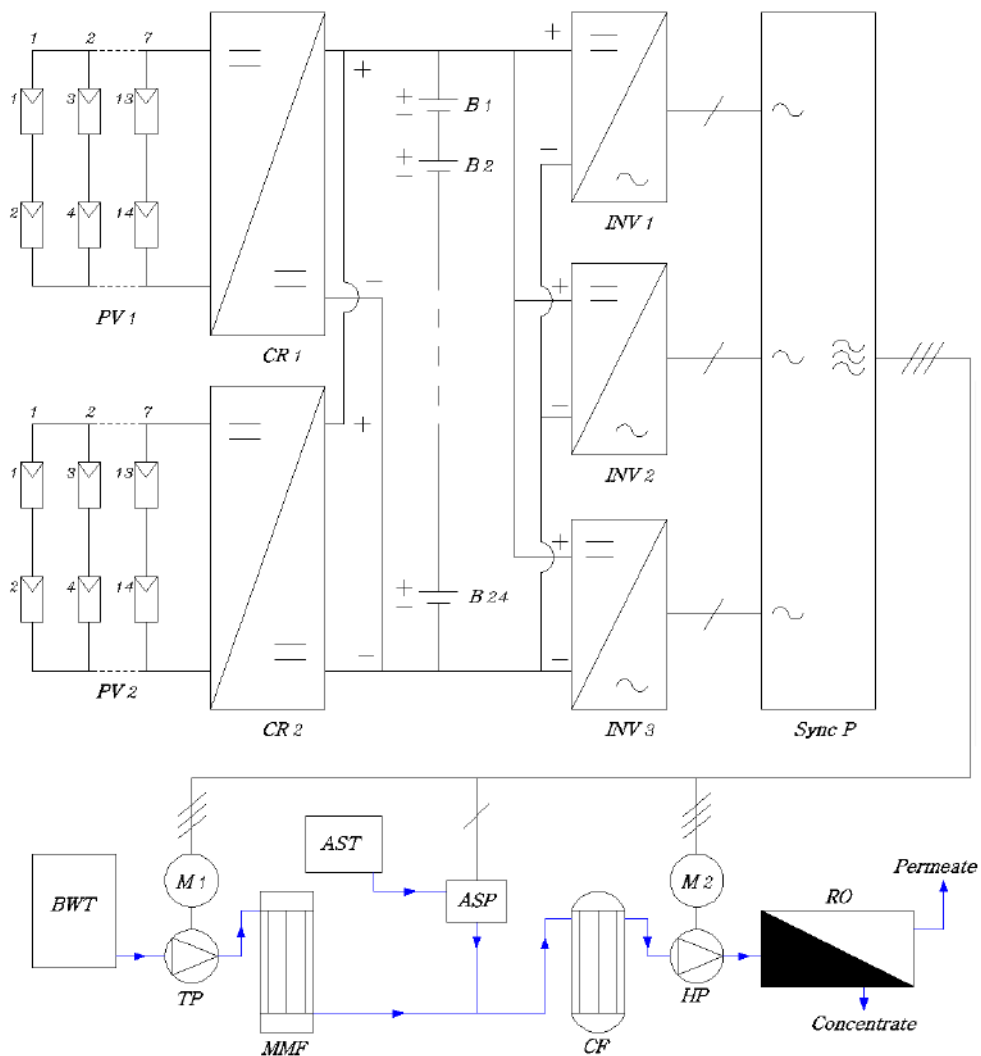


Figure (6.8): Schematic diagram for Az Zubeidat project.

Where:

<ul style="list-style-type: none"> •PV1, PV2: Photovoltaic arrays. •CR1, CR2: Battery charge regulators. •B1-B24: Storage battery cells. •NV1, NV2, NV3: DC/AC Inverters. •Sync p: Synchronizing control panel. •M1-TP: Transfer motor pump. 	<ul style="list-style-type: none"> •M2-HP: RO HP motor pump. •AST: Anti scaling tank. •ASP: Anti scaling pump. •BWT: Brackish water storage tank. •MMF: Multimedia filter. •CF: Cartridge filter. •RO: RO Vessels containing the membranes
--	---

Selection of components:

a. RO Membrane.

RO Membrane type selected is spiral wound element FILMTEC LE-4040 (40 inch length and 4 inch diameter), which is known of highest performance at lowest feed pressure and thereby of lowest energy consumption.

The specifications of the selected membrane are summarized in the followings:

- Hard fiberglass
- The active area of one membrane element = 7.2 m^2
- Salt rejection = 99%
- Maximum pressure = 10.3 bar
- Maximum feed flow rate = $9.5 \text{ m}^3/\text{day}$
- Maximum pressure drop = 1.03 bar

In this project installed three vessels connected in series, each vessel contain two RO membranes connected in series also, this means there are six RO membranes built in this project with the above specifications.



Figure (6.9): Photographic picture of RO vessels in Az Zubeidat project.

b. Transfer motor pump

This pump is used to transfer the raw water from the BW storage tank to the inlet of MMF, the TDS of the raw water is equal to 2681 mg/L corresponds to an osmotic pressure of 2.04 bar. Taking into consideration the pressure drop on the MMF and CF and considering a safety factor of 1.1, it was concluded to select a three phase motor centrifugal pump specified as follows:

2.5 m³/h at 3.79 bar, which corresponds to a rated output of 2.5 m³/h at 38.65 m head. (1bar = 10.199 m head).

Specifications of transfer motor pump that found to be the most suitable one for this purpose:

- Pump type: Grundfos (Denmark), CR2- 70.
- Material: stainless steel.

- Q-H performance: 3m³/h at 42.7 m head.
- Supply voltage: 3x380 V
- Speed: 2864 rpm, 50 Hz.
- Motor power: 750 W.
- Efficiency: 42%.
- PF: 0.82.



Figure (6.10): Photographic picture of TP in Az Zubeidat project.

c. HP pump (RO pump)

This pump is installed between the CF and the RO vessels containing the membranes. It pumps the water from output of the CF into the RO vessels.

Depending on ROSA program, feed flow equal 2.36 m³/h and feed pressure equal 10.75 bar, and respecting a safety factor of 1.1, it was concluded to select a three phase induction motor pump specified as:

2.5 m³/h at 11.825 bar, which corresponds to a rated output of 2.5 m³/h at 120.61 m head.

A three phase induction motor HP pump type Grundfos was found to be the most suitable one for this purpose.

Specifications of RO HP motor pump:

- Pump type: Grundfos (Denmark), CRI3- 29
- Material: stainless steel housing and impeller.
- Q-H ratings: 3m³/h at 140 m. head.
- Supply voltage: 3x380V.
- Speed: 2900 rpm, 50 Hz.
- Motor power: 2.431 kW.
- Efficiency: 42%.
- PF: 0.84



Figure (6.11): Photographic picture of HP motor pump in Az Zubeidat project.

d. Chemical injection pump (anti scaling pump)

A scale inhibitor injection system is installed consisting of one tank with 35 liter capacity complete with cover and a solenoid driven diaphragm pump. The injection occurs at the inlet of the cartridge filter.

Specifications of Anti scaling pump:

- Pump type: Grundfos.
- Material: PVC/ VTC.
- Maximum flow: 1.89 L/h.
- Maximum head: 56m.
- Supply voltage: 220Vac, 50 Hz.
- Motor power: 350 W.



Figure (6.12): Photographic picture of anti-scaling pump in Az Zubeidat project.

e. Multimedia filter

The removal of suspended and colloidal solids by media filtration is based on their deposition on the surface of filter grains while the water flows through a bed of these grains (filter media). The quality of the filtrate de-

depends on the size, surface charge and both suspended solids and filter media as well as on the water analysis and operational parameters.

The effective grain size for fine sand filter is in the range of 0.35-0.5 mm, and 0.7-0.8 mm for anthracite filter. During separation, influent water to be filtered enters at the top of the filter, percolates through the filter bed and is drawn off through the collector system at the bottom. Periodically when the differential pressure increase between inlet and outlet, the filter has to be back washed and rinsed to carry away the deposited materials.

Specifications of MMF:

- Operation tap: Multi stage auto flash.
- Column: Armored fiber glass.
- Column dimensions: 16 inch×65inch.
- Columns count: 2.
- Bed type1: multilayer quartz.
- Bed type2: activated carbon.
- Supporting bed: Basalt.



Figure (6.13): Photographic picture of MMF in Az Zubeidat project.

f. Cartridge filter

CF can provide additional particulate control. Cartridge filtration process often provides the last line of defense against suspended solids forming in RO processes. It prohibits the pass of suspended particles such as clay, silt, sand, or chemical impurities to the RO membranes. Two filters were installed in the system each of 20inch length and 4inch diameter.

Specifications of Cartridge filter:

- Type: DGD 7525-BB/DGD5005-BB.
- BB filter housing with Micronics filters: 5 microns.
- Filter housing: Tough poly ethylene.
- Housing length: 20 inch.
- Housing amount: 4.
- Feed opening: 1inch.
- Filter type: Poly propylene.
- Filter diameter: 4 inch.
- Candle amount: 4.



Figure (6.14): Photographic picture of Cartridge filters in Az Zubeidat project.

g. Sizing the PV power system.

The RO desalination system is powered by a solar PV power system (PV). Determining the peak power of the PV Generator depends on the daily electric load to be supplied and on the annual average of daily solar radiation in the area. Considering the input power of the transfer pump, the RO-HP pump and the anti-scaling pump we obtain a total load power (P_{LT}) amounting to:

$$P_{LT} = P_{TP} + P_{HPP} + P_{ASP} = 750 + 2431 + 350 = 3530 \text{ W} \quad (6.1)$$

Considering a daily operation of the system amounting to $t_d = 6.5 \text{ h}$, we obtain the total daily load energy (E_{dl}):

$$E_{dl} = P_{LT} \times t_d \quad (6.2)$$

$$E_{dl} = 3531 \times 6.5 = 22952 \text{ Wh/day} \quad (6.2^*)$$

Assuming an efficiency of inverter (η_{in}) is 95% and an efficiency of battery charge controller (η_{cc}) is 95% then, the daily energy (E_{PV}) necessary from the PV generator is:

$$E_{PV} = E_{dl} / (\eta_{in} \times \eta_{cc}) \quad (6.3)$$

$$E_{PV} = 22952 / (0.95 \times 0.95) = 25431 \text{ Wh/day.}$$

The annual daily average of solar radiation in the west bank amounts to $5400 \text{ Wh/m}^2\text{-day}$ which corresponds to 5.4 peak sun hours (PSH).

Therefore, the necessary peak power of the PV generator while respecting a safety factor of 1.12 is obtained as (P_{PV}):

$$P_{PV} = (E_{PV} / \text{PSH}) \times 1.12 \quad [37] \quad (6.4)$$

$$P_{PV} = (25431 / 5.4) \times 1.12 = 5274.5 \text{ W}_p \quad (6.4^*)$$

Using the PV module type SCHOTT 185-Gernany rated at 185 W_p (P_M), the number of necessary modules (N_M) is obtained as:

$$N_M = P_{PV}/P_M \quad (6.5)$$

$$N_M = 5274.5/185 = 28 \text{ module.}$$

This PV module has the following specifications at standard conditions: open circuit voltage V_{oc}= 45V, short circuit current I_{sc}=5.43A, voltage at maximum power point V_{mmp}=36.33V, current at maximum power point I_{mpp}=5.1A, peak efficiency η=14.1 and nominal operating cell temperature NOCT= 46 °C.

Az Zubeidat project produce 10m³ of permeate per day, so by dividing the results of equations (6.2*) and (6.4*) by 10m³/day, the results shows that 1m³ of permeate water produced from brackish water with a TDS 2681mg/L, requires 2.3 kWh which is represented at G_{av}=5.4 kWh/m²-day approximately in 450 W_p PV cells.

The nominal battery voltage was selected to be V_B = 48 V. This selection requires connecting each 2 PV modules in series to build 14 strings connected in parallel. Figure (6.8) shows the interconnections of the PV modules with the battery charge controllers, the battery bank, the inverters and the three pumps which constitute the main electrical components of the desalination system, as seen also, each 14 PV modules are connected to one charge controller, the output of the two charge controller are connected in parallel to the battery bank consisting of 24 battery cells, to build a nominal voltage of 48 VDC.

The 28 PV modules are installed on the roof of the BW tank in two arrays as shown in the photographic picture illustrated in figure (6.15), the front array consists of 12 PV modules and the rear of 16 PV modules , the distance between them was calculated to avoid shadowing during the peak sun hours according the following equation [44]:

$$x=a[\sin\beta\times\tan(23.5+Lat)+\cos\beta] \quad (6.6)$$

Where

x: is the distance between the two PV arrays facing south.

a: is the length of the PV array in front of the second array installed to the north, its equal 1.80 m.

β : is the tilt angle of the PV array on a horizontal level amounting to 45°.

Lat: is the latitude of the project site, its equal 32°.

After solving equation (6.6) found that $x = 3.12$ m

The two PV arrays were installed on the roof of the BW tank at a height of 8m above earth level which protects the PV modules against damage and dust accumulation on their surfaces.



Figure (6.15): Photographic picture of PV arrays in Az Zubeidat project.

h. Sizing the storage battery bank.

In this thesis a PV system with battery bank not without battery bank is chosen for the following reasons:

1. Energy Storage Capacity and reliability: Improve the reliability of the system because the excess energy is stored in the battery bank, and this energy is delivered to the load when the solar energy is not available or not sufficient (at night and cloudy days).
2. Voltage and Current Stabilization: to supply power to electrical loads at stable voltages and currents, by suppressing or 'smoothing out' transients that may occur in PV systems.

3. Supply Surge Currents: to supply surge or high peak operating currents to electrical loads or appliances, and ability to meet momentary peak power demands.

The ampere-hour capacity C_{Ah} of the battery bank (A group of batteries connected in series, parallel, or both) is obtained from the following equation.

$$C_{Ah} = \frac{E_d}{DOD \times \eta_B \times V_B} \quad (6.7)$$

Where:

E_d : is the daily load energy at the input of inverter

DOD: is the permissible depth of discharge.

η_B : is the ampere hour efficiency of the battery cell.

V_B : is the nominal voltage of the battery bank. Substituting the corresponding values of these variables we obtain:

$$C_{Ah} = \frac{24159.5}{0.75 \times 0.82 \times 48} = 818.40 \text{ Ah}$$

The watt hour capacity C_{wh} of the storage system is obtained as:

$$C_{wh} = C_{Ah} \times V_B \quad (6.8)$$

$$C_{wh} = 818.4 \times 48 = 39283 \text{ W}$$

24 battery cells type VARTA PZS875 was selected to be connected in series as shown in figure (6.16) to build a nominal battery voltage of 48V. Each battery cell is rated at 2V/875 Ah which represents a total energy capacity of $C_{wh} = 42 \text{ kWh}$.



Figure (6.16): Photographic picture of Battery bank in Az Zubeidat project.

i. Battery charge controller

This is a DC/DC converter that obtains the output voltage of the PV generator and regulates it to be appropriate for the nominal charge voltage of the battery. Its output voltage is adjustable within a hysteresis with minimum and maximum values. This controller protect the battery bank against deep discharge and extremely overcharge that leads to gas production and therefore it elongates the life time of the battery. Usually the nominal power of this controller is equal to the peak power of the PV generator.

Two controllers from Morningstar company each rated at 48V/2.5kW where used. Each controller is connected to the output of one PV array consisting of 14 PV modules, and then the outputs of the two controllers are connected in parallel as shown in figure (6.8).



Figure (6.17): Photographic picture of DC/DC converters in Az Zubeidat project.

j. DC/AC inverters.

The inverter converts DC voltage of the battery bank and the output voltage of the PV generator into three phase sinusoidal voltage with 50 Hz, The rated power of the inverter must be at least equal to the total input power of the load consisting mainly of the transfer pump, the HP RO pump and the anti-scaling pump, amounting totally to about 4kW.

Three equivalent inverters (type STUDER module XTM2600-48) where used because one three phase inverter rated at 380V/6kVA was not found. Each of the three inverters is rated at 48VDC/230VAC. The out puts of the three inverters are connected in Y-connection and synchronizing control panel to build a three phase system with 380V line to line voltage for supplying the transfer pump and RO motor pump and to supply the anti scaling pump with 220 V single phase voltage.



Figure (6.18): Photographic picture of DC/AC inverters in Az Zubeidat project.

k. Instrumentation and measuring system.

The RO desalination system is equipped with an instrument panel which includes a conductivity meter for permeate, flow meters and pressure gauges. The system includes also a data acquisition system which measures and records continuously the global solar radiation on PV modules, the ambient temperature, the PV cell temperature, the input and output of the PV generators, the input and output of the battery bank, as well as the output parameters of the three phase inverters. The measured values are stored as data file for later evaluation. Furthermore the measuring system includes a telemetry system which enables at the same time illustrating the measuring data on the computers of the An Najah National University.

6.3 Heavy metals content in feed, permeate and concentrate for Az Zubeidat project

Laboratory tests were conducted for water samples that taken from Az Zubeidat project, two samples taken from tank (feed water), two samples taken from RO system product water, and two samples taken from concentrate water at different periods (one in June 2011, and another in September 2012). Heavy metals test was conducted by inductive coupled plasma-mass spectrometry ICPMS instrument, in WESI laboratories, in An Najah National University, it shows that the main metals in well water are calcium, sodium and magnesium; these metal are not very dangerous for the human health but high concentrations may affect some body organs; such as kidney and liver. The existence of some common heavy metals was in acceptable level of concentrations or zero. High salt concentration act as a preservative of water from bacterial growth and this explain why there is no bacterial growth in well and water tank. For fresh water produced from RO system the TDS concentration is very law; less than 50 mg/L, the main metals in this water were calcium, sodium and magnesium as in BW but in very low concentrations. The human body needs for some metals, but in general water is not the main source of these metals. Some consumers prefer moderate concentrations of metals salts for a good taste of water, in Az Zubeidat village the consumers prefer to take water as it produced from the RO system with no additives. Some dangerous metals concentration such as lead, cadmium and arsenic were zero that make the water much safer for inhabitants.

Table (6.2): Heavy metals content in feed, permeate and concentrate from Az Zubeidat project (September 2012).

Elements	Feed mg/L	Permeate mg/L	concentrate mg/L
Li	0.10	0.00	0.20
Be	0.00	0.00	0.00
B	0.85	0.35	0.00
C	513.45	1.40	431.40
Na	425.90	6.44	776.00
Mg	128.60	0.00	304.55
Al	0.25	0.00	0.00
Si	12.50	0.00	0.00
P	0.65	0.00	1.90
Cl	1462.85	20.90	3403.55
K	30.90	0.38	47.85
Ca	146.50	0.00	200.30
Sc	0.05	0.00	0.00
Ti	0.15	0.00	0.00
V	0.00	0.00	0.05
Cr	0.10	0.00	0.05
Mn	0.00	0.00	0.00
Fe	5.15	0.00	0.00
Co	0.00	0.00	0.00
Ni	0.05	0.00	0.05
Cu	0.10	0.00	0.05
Zn	26.95	0.00	0.40
As	0.00	0.00	0.00
Se	0.00	0.00	0.00
Br	0.00	0.24	12.55
Pb	0.00	0.00	0.00
Cd	0.00	0.00	0.00
Sn	0.00	0.00	0.00
Ba	0.00	0.00	3.20

Chapter Seven

Economic Analysis and Environmental Impact of Using BWRO Desalination System Powered By PV System

7.1 Economic Analysis of Using BWRO Desalination System Powered by PV System

7.1.1 Economic analysis of using BWRO desalination system powered by PV system with battery bank

Introduction

Individuals, small business owners, large corporation presidents, and government agency heads are routinely faced with the challenge of making decisions when selecting one alternative over another. To overcome this challenge and choose a suitable alternative, there is a need to economic analysis; it is the essential factor and heart of making decisions, beside another factors like environment, social, political, ethical, health, safety, and sustainability.

Steps of work in this section:

1. Cash flow analysis
2. Economic analysis using Rate of Return (ROR) method.
3. Evaluate Az Zubeidat project depends on ROR results.

7.1.1.1 Cash flow analysis for Az Zubeidat project

Cash Flow: It's the estimated outcomes (costs) and incomes (revenues) of money over a stated time period.

In this section the cash flow charts will show the incomes money and outcomes money for Az Zubeidat project.

a. Outcomes for Az Zubeidat project.

Table (7.1) shows all outcomes for Az Zubeidat project, like capital cost, operating and maintenance (O&M) cost.

Table (7.1) Outcomes for Az Zubeidat project.

Component	Quantity	Unit price \$	Life time year	Total price \$
PV module (185W)	5180 WP	1/Wp	20	5180
Batteries (2V/875Ah)	24	437.5	10	10500
Charge Controller 2.5 kW	2	1500	20	3000
Inverter 3.6 kW	3	2100	20	6300
Installation Material	---	---	20	1000
Installation (electrical & mechanical) Cost	---	---	---	2000
Transfer pump	1	2400	20	2400
High pressure pump	1	3500	20	3500
Anti-scaling pump	1	1000	20	1000
Multimedia filter	2	1100	5	2200
Cartridge filter	2	600	5	1200
RO membrane vessel	3	3500	5	10500
Piping, valves, gages	1	3900	20	3900
Electric control panel	1	1200	20	1200
Instrument control panel	1	2000	20	2000
Cleaning system	1	1500	20	1500
Steel structure painted by epoxy coated	1	1400	20	1400
Total capital cost of the system				58780\$
Operating and maintenance cost/year	6%from capital cost			3527\$

-The land of project is free of money.

b. Incomes for Az Zubeidat project:

Incomes divided into two parts:

1. Salvage value: it's estimated residual value of a depreciable asset or property at the end of life time of the project.

In this project salvage value suggested to be 10% of total capital costs, then
salvage value = $0.10 \times 58780 = 5878\$$

2. Annual Saving

The annual saving in money for this project can be calculated by using the following formula:

$$\text{Annual saving} = Q_p \times t_d \times p \times D \quad (7.1)$$

Where:

Q_p : number of cubic meter of permeates water produced from project per hour (m^3/h), its equal $1.538 \text{ m}^3/\text{h}$.

t_d : number of operation system hour's in a day, its equal 6.5 h/day .

$Q_p \times t_d$ equal to number of cubic meter of permeates water produced from project per day $= 1.538 \times 6.5 = 10 \text{ m}^3$

p : cost of one m^3 from potable water from water delivery trucks.

From calling number of water delivery truck drivers from different regions the following information was found:

- Cost of water delivery truck (10m^3) to atouf village = (150-220) NIS
- Cost of water delivery truck (10m^3) to Almaleh village = (220-250) NIS
- Cost of water delivery truck (10m^3) to Az Zubeidat village = (170-200) NIS.
- Cost of water delivery truck (10m^3) to beir albash village = (175-200) NIS.

The average cost of all regions is approximately = $180 \text{ NIS}/10\text{m}^3$ of fresh water.

$$\text{Then cost of } 1\text{m}^3 = 180/10 = 18\text{NIS}/\text{m}^3 / (3.55\$/\text{NIS}) = 5.07\$/\text{m}^3$$

$$c = 5.07\$/\text{m}^3$$

D: number of days per year that the system is operated (350).

From equation (7.1),

$$\text{Annual saving} = 1.538 \times 6.5 \times 5.07 \times 350 = 17740 \$/\text{year}.$$

Then The Cash flow chart for Az Zubeidat project is shown in Figure

(7.1)

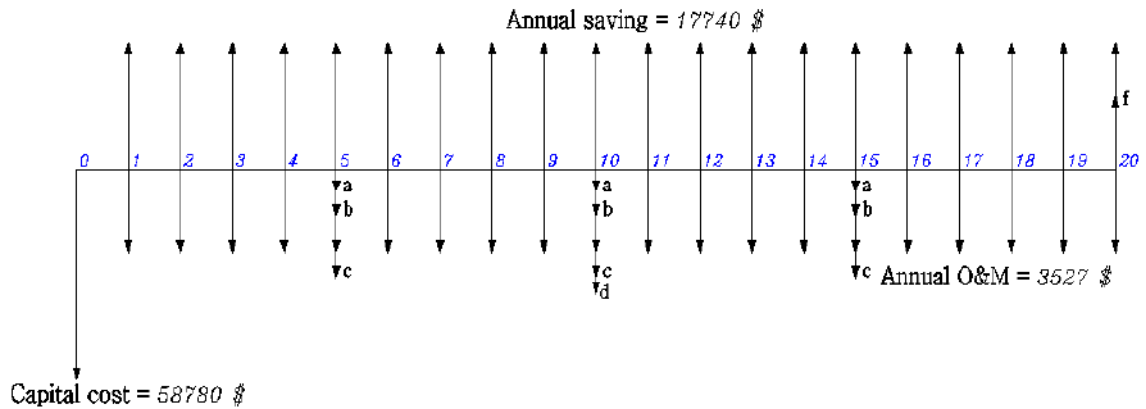


Figure (7.1): Cash flow chart for Az Zubeidat project.

Where:

a: CF replacement = 1200\$.

b: MMF replacement = 2200\$.

c: RO membrane replacement = 10500\$.

d: Battery replacement = 10500\$.

f: Salvage value = 5878\$.

7.1.1.2 Economical analysis using rate of return (ROR) method

It is the effective annual interest rate earned on an investment and It's one of the important economic methods to justify whether the project is feasible or not.

We can find ROR by using the following equation.

$$PW_{\text{income}} - PW_{\text{outcome}} = 0 \quad (7.2)$$

Where:

- PWincome is mean present worth income (positive Value in cash flow) and the formula for it is :

$$\text{PWincome} = \text{annual saving (P/A, } i^*, 20) + \text{Salvage value (P/F, } i^*, 20)$$

(7.3)

Where:

- $(\text{P/A, } i^*, 20)$: find present value from annual value at the interest rate of $i^*\%$ and at the life time of 20 years.
- $(\text{P/F, } i^*, 20)$: find present value from future value at the interest rate of $i\%$ and at the life time of 20 years.
- PWoutcome it mean present worth outcome (negative value in cash flow), the formula for it.
- $\text{PWoutcome} = \text{annual cost(P/A, } i^*, 20) + \text{capital investment}$ (7.4)
- 20 it's the lifetime in years of the project.

For Az Zubeidat project we use equation 1 to find ROR, and other values from cash flow figure (7.1):

To find PWincome and PWoutcome, we use equations (7.3) and (7.4) as follows:

$$\text{PWincome} = 17740(\text{P/A, } i^*, 20) + 5878(\text{P/F, } i^*, 20)$$

$$\begin{aligned} \text{PWoutcome} = & 58780 + 3527(\text{P/A, } i^*, 20) + (1200 + 2200 + 10500)(\text{P/F, } i^*, 5) + \\ & (1200 + 2200 + 10500)(\text{P/F, } i^*, 10) + (1200 + 2200 + 10500)(\text{P/F, } i^*, 15) + \\ & 10500(\text{P/F, } i^*, 10). \end{aligned}$$

From equation (7.2)

$$\{17740(P/A, i^*, 20) + 5878(P/F, i^*, 20)\} - \{58780 + 3527(P/A, i^*, 20) + (1200 + 2200 + 10500)(P/F, i^*, 5) + (1200 + 2200 + 10500)(P/F, i^*, 10) + (1200 + 2200 + 10500)(P/F, i^*, 15) + 10500(P/F, i^*, 10)\} = 0 \text{ then,}$$

ROR = $i^* = 20\%$ after solving the equation by using appendix A2.

- Calculate the cost of 1 m³ permeate water produce by Az Zubeidat project:

To find the cost of 1 m³ permeate water produce by Az zubeidat project the annuity cost which bases on Life Cycle Cost for annual production of the project must be known.

Life Cycle Cost in Annual worth = Investment Cost in annual worth + annual cost + battery replacement in annual worth + CF replacement in annual worth + MMF replacement in annual worth + RO membrane vessels replacement in annual worth - Salvage Value in annual worth .

$$LCC(AW) = C_{\text{investment.AW}} + C_{\text{o\&m}} + C_{\text{bat rep.AW}} + C_{\text{CF rep.AW}} + C_{\text{MMF rep.AW}} + C_{\text{RO m rep.AW}} - C_{\text{salvage.AW}} \quad (7.5)$$

$$\text{cost of } 1\text{m}^3 \frac{\$}{1\text{m}^3} = \frac{\text{Life Cycle Cost (AW)}}{\text{Yearly permeate water prouduction}} \quad (7.6)$$

6% interest rate (as shown in appendix A1) is used to find AW of the LCC for the project,

$$LCC(AW) = 58780(A/P, 6\%, 20) + 3527 + 13900(P/F, 6\%, 5)(A/P, 6\%, 20) + 13900(P/F, 6\%, 10)(A/P, 6\%, 20) + 13900(P/F, 6\%, 15)(A/P, 6\%, 20) + 10500(P/F, 6\%, 10)(A/P, 6\%, 20) - 5878(A/F, 6\%, 20).$$

$$LCC(AW) = 58780 \times 0.08718 + 3527 + 13900 \times 0.7473 \times 0.08718 + 13900 \times 0.5584 \times 0.08718 + 13900 \times 0.4173 \times 0.08718 + 10500 \times 0.5584 \times 0.08718 - 5878 \times 0.02718.$$

$$LCC(AW) = 11090\$$$

$$\bullet \text{cost of } 1 \text{ m}^3 (\$/\text{m}^3) = 11090/3500 = 3.17 \$/\text{m}^3$$

7.1.1.3 Evaluate Az Zubeidat project depending on ROR results.

Comparing with Cairo-Amman bank that give maximum ROR = 3% on 60000\$ in 20 years (the value of capital cost in this investment), it's clear that ROR of this project 20% is high, then it will justify and encourage the investment in this kind of projects (BWRO desalination powered by PV system in remote area that lack of fresh water network, and electrical network), therefore this Project is feasible, and there is high annual saving from this project.

7.1.2 Economic analysis of using BWRO desalination system powered by PV system without battery bank

Not the aim of this section is to study the feasibility of the project, because the project is feasible with battery bank, then logically it is more feasible without battery bank (operate the system during sun shine hours) because the capital cost is decreased by eliminate batteries fixed and replacement cost, and charge controller cost, but the aim of this section is to study the economic impact on Az Zubeidat project when we build it without battery bank, the following sections show the economic impact on capital cost, cash flow chart, all project cost during the total life time, and cost of 1 m³ of product water.

7.1.2.1 Economic impact on capital cost when we build Az Zubeidat project without battery bank

When we build Az Zubeidat project without battery bank we eliminate the batteries fixed and replacement cost, and charge controller cost from capital cost then it will be become:

Capital cost without B = capital cost (with B) - batteries cost - charge controller cost.

Capital cost (without B) = $58780 - 10500 - 3000 = 45280$ \$ then;

Percentage of decrease = $(\text{Capital cost (without B)} - \text{capital cost (with B)}) / \text{Capital cost (without B)}$

percentage of decrease = $(58780 - 45280) / 58780 = 0.23 = 23\%$ then when we build Az Zubeidat project without battery bank we decrease 23% from capital cost, In other words, battery bank represent 23% from capital cost.

7.1.2.2 Economic impact on cash flow when we build Az Zubeidat project without battery bank.

Economic impact on cash flow summarized in figure (7.2):

1. Capital cost become 45280\$.
2. Salvage value = $0.10 \times \text{capital cost} = 0.10 \times 45280 = 4528$ \$
3. O&M cost remain the same.
4. Battery replacement cost eliminated and another replacement costs remain the same.

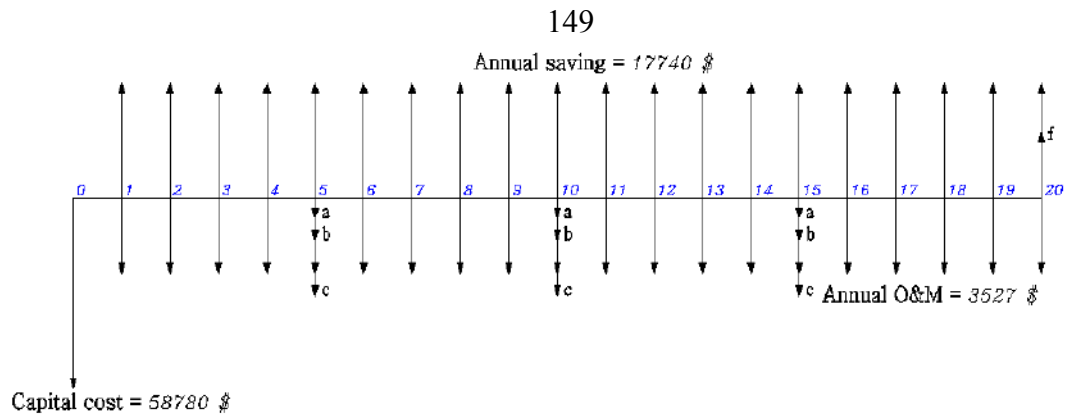


Figure (7.2): Cash flow chart for Az Zubeidat project without battery bank.

Where:

- a: CF replacement = 1200\$.
- b: MMF replacement = 2200\$.
- c: RO membrane replacement = 10500\$.
- f: Salvage value = 4528\$.

7.1.2.3 Economic impact on all project cost during the total life time when we build Az Zubeidat project without battery bank.

After using equation (7.5) to calculate LCC (AW) on cash flow in figure (7.2) the LCC (AW) = 8150\$ then;

$$\text{Percentage of decrease} = \frac{\text{LCC (AW) (without B)} - \text{LCC (AW) (with B)}}{\text{LCC (AW) (without B)}}$$

percentage of decrease = $(11090 - 8150) / 11090 = 0.265 = 26.5\%$ then when we build Az Zuaeidat project without battery bank we decrease 26.5% from all project cost during the total life time, In other words, battery bank represent 26.5% from all project cost during the total life time.

7.1.2.4 Economic impact on cost of 1m³ of product water when we build Az Zubeidat project without battery bank

After using equation (7.6)

$$\text{The cost of 1 m}^3 \text{ of product water (C}_{pw}) = 8150 / 3500 = 2.33\$/\text{m}^3$$

Percentage of decrease = $(C_{pw} \text{ (without B)} - C_{pw} \text{ (with B)}) / C_{pw} \text{ (without B)}$

Percentage of decrease = $(3.17 - 2.33) / 3.17 = 0.265 = 26.5\%$ then when we build Az Zubeidat project without battery bank we decrease 26.5% from the cost of 1 m^3 of product water.

7.1.2.5 Amount of potable water produced from Az Zubeidat project if operate it without battery bank

If operate Az Zubeidat project at solar energy only during the day without using battery bank the average monthly amount of produced potable water can be calculated from the following equation:

$$A_{pw} = (PSH_m / PSH) \times 10 \text{ where:}$$

A_{pw} : Amount of produced potable water in chosen month.

PSH_m : The Peak Sun Hours in chosen month (from section (4.1)).

PSH : The Average Peak Sun Hours around the year.

10 m^3 : The average potable water produced from Az Zubeidat project around the year (calculated at $PSH = 5.4 \text{ h}$).

Example: In January the $A_{pw} = (3.01 / 5.4) \times 10 = 5.57 \text{ m}^3$.

Table (7.2) shows the amount of produced potable water in every month.

Table (7.2): Monthly amount of produced potable water from Az Zubeidat project

Month	m^3
January	5.57
February	6.26
March	9.35
April	12.4
May	13
June	15.44
July	14.24

	151
August	13.5
September	10.96
October	8.6
November	6
December	4.9

Table (7.2) shows:

1. In June the largest amount of potable water is produced (15.44m^3), thus 20 m^3 storage tank for produced potable water must be installed.
2. Average amount of produced potable water = (summation of monthly amount of produced potable water)/12 then,

Average amount of produced potable water around the year = $120.22/12 = 10\text{ m}^3/\text{day}$

7.2 Environmental Impact of Using Solar PV Systems to Powered BWRO Desalination System

7.2.1 Environmental impacts of solar power

Introduction

The PV technologies have distinct environmental advantages over conventional technologies for electricity generation. The operation of PV systems does not produce any noise, toxic-gas emissions, and greenhouse gases. PV energy not only can help meet the growing worldwide demand for electricity, but it can do so without incurring the high economic and environmental costs of installing power lines or burning fossil fuels. Relative to burning coal, every giga watt-hour of electricity generated by PV would prevent the emission of about 10 tons of SO_2 , 4 tons of NO_x , 0.7 tons of particulates (including 1 kg of Cd and 120 kg of As), and up to 1000 tons of CO_2 . [45]

a. Land use

Depending on their location, larger utility-scale PV solar facilities can raise concerns about land degradation and habitat loss. Total land area requirements estimates from 8-13 m² per 1 kW_p, unlike wind facilities, there is less opportunity for PV solar projects to share land with agricultural uses. However, land impacts from utility-scale PV solar systems can be minimized by sitting them at lower-quality locations such as brownfield, abandoned mining land, or existing transportation and transmission corridors. Smaller scale solar PV arrays, which can be built on homes or commercial buildings, also have minimal land use impact [46].

b. Water use

Solar PV cells do not use water for generating electricity. However, as in all manufacturing processes, some water is used to manufacture solar PV components [46].

c. Hazardous materials

The PV cell manufacturing process includes a number of hazardous materials, most of which are used to clean and purify the semiconductor surface. These chemicals, similar to those used in the general semiconductor industry. The amount and type of chemicals used depends on the type of cell, the amount of cleaning that is needed, and the size of silicon wafer. Workers also face risks associated with inhaling silicon dust, Table (7.2) shows some hazardous materials used in current PV manufacturing: [45]

Table (7.2): Some hazardous materials used in current PV manufacturing.

Material	Chemical formula	Critical Effects
Arsine	AsH ₃	Blood, kidney
Arsenic compounds	-----	Cancer, lung
Cadmium compounds	-----	Cancer, kidney
Carbon tetrachloride	CCl ₄	Liver, cancer, green house gases
Chloro silanes	H ₃ ClSi	Irritant
Copper	Cu	Irritant, liver, kidney
Diborane	B ₂ H ₆	CNS*, pulmonary
Germane	GeH ₄	Blood, CNS, kidney
Hydrogen	H	Fire hazard
Hydrogen fluoride	HF	Irritant, burns, bone, teeth
Hydrogen selenide	H ₂ Se	Irritant, GI, flammable
Hydrogen sulfide	H ₂ S	Irritant, CNS, flammable
Indium compounds	-----	Pulmonary, bone, GI
Lead	Pb	CNS, GI, blood, kidney, reproductive.
Nitric acid	HNO ₃	Irritant, corrosive.
Phosphine	PH ₃	Irritant, CNS, GI**, flammable.
Phosphorous oxychloride	POCl ₃	Irritant, kidney.
Selenium hydroxide	Se(OH) ₂	Irritant
Silane	SiH ₄	Irritant, fire, explosion hazard.
Tellurium compounds	-----	CNS, cyanosis, liver.
Silicon tetrachloride	SiCl ₄	Irritant, lung.

*(CNS): The central nervous system is the part of the nervous system that integrates the information that it receives from and coordinates the activity of all parts of the bodies of animals that is, all multicellular animals except radially symmetric animals such as sponges and jellyfish.

** (GI): The Human Gastrointestinal Tract.

d. Hazardous waste

Solar PV panels may contain hazardous materials that could be released when a panel is damaged or disposed it improperly [47].

Lead-acid batteries used in Az Zubeidat project can cause environmental and health problems if disposed it improperly because it is contain chemicals that have the potential to be hazardous to our health and the environment. The batteries contain lead, a highly toxic metal, and sulfuric acid, a corrosive electrolyte solution. Since both of these materials are classified as hazardous, it is very important that the battery be handled properly [48]. Contact with the sulfuric acid solution may lead to irritation or burns to the skin, or irritation to the mucous membranes of the eyes or the upper respiratory system [48].

Symptoms of low-level lead exposure include fatigue, impaired central nervous system functions, and impaired learning. Severe lead poisoning can result in coma, convulsions, irreversible mental retardation, seizures, and even death [48].

If lead-acid batteries are disposed of in a solid waste landfill or illegally dumped, the lead and sulfuric acid can seep into the soil and contaminate ground water, potentially affecting the quality of our drinking water supply. If the batteries are disposed of near rivers, streams, lakes, or marine waters, the lead and sulfuric acid can also threaten aquatic life [48].

e. Visual

One person's beauty is another person's eyesore. For some, solar panels evoke positive feelings, even when set in a natural landscape. For others,

the sight of a solar panel invading a pristine desert environment is gut wrenching [47].

7.2.2 The environmental impact of using PV systems powered BWRO system.

Due to the replacement of the water delivery tanks by desalination BW using RO membrane powered by PV system, there are saving in diesel fuel, then there are saving in CO₂ emission to atmosphere, the following equation is used to calculate the amount of saving in CO₂ (kg):

Annual saving in CO₂(kg/year)= Z×D×X Where:

Z: saving in diesel per day (l/day)

D: number of days per year

X: amount of CO₂ produced by burned of 1 liter diesel (kg/L)

By calling water delivery truck drivers, they said that the truck consume 1 liter per 4 km in average , and the distance from fresh water supply station to atouf village about 20 km, the distance from fresh water supply station to almaleh village about 45 km, the distance from fresh water supply station to Az Zubeidat village about 15 km, the distance from fresh water supply station to beir albasha village about 15 km, in average the distance that the truck traveled per day is about 18 km, then

$$Z = (18\text{km/day} \times 1 \text{ L}) / 4\text{km} = 4.5 \text{ L/day}$$

X= 3.2 kg CO₂/1 kg diesel [49], when;

Diesel weight = (0.820 kg/L - 0.845 kg/L) in average 0.8325 kg/L [50], then; X= 2.664 kg CO₂/1 liter diesel.

$$\text{Annual saving in CO}_2 = 4.5 \times 350 \times 2.664 = 4.195 \text{ tonCO}_2/\text{year}.$$

7.2.3 Environmental impacts of concentrate (brine) that result from Az Zubeidat project

From table (6.5) TDS for concentrate from Az Zubeidat project is above 6000 mg/L and its produce annual concentrate volume (m^3/year) as following equation:

$$Q_{ac} = Q_f \times (1-R) \times t_d \times D$$

Where:

Q_{ac} : annual concentrate flow in (m^3/year).

Q_f : feed flow in (m^3/h).

t_d : number of hours per day.

D : number of days per year.

Then $Q_{ac} = 2.36 \times (1-0.65) \times 6.5 \times 350$.

$Q_{ac} = 1879 \text{ m}^3/\text{year}$.

Considering that the TDS of brine about 6000 mg/L, the outlined brine solution contains about 11274 kg/year.

The environmental impact of this high salt concentrate amount if it is left to flow in the ground as follows:

- a. Effect on the flora and fauna of the directly contaminated area. Increased salinity pushes living organisms to the extremes of their tolerance limits.
- b. Effect on groundwater in the area and will make it more salty.

Thus the best option to dispose this salt concentration by continue concentrating by means of natural evaporation until getting a solid waste that can be valued or directly managed and exploited by an authorized chemical

company. The main purpose of applying natural evaporation is to reduce the energy consumption of the treatment and the associated costs.

Chapter Eight

Conclusion And Recommendation

8.1 Results and Conclusions

- A considerable volume of brackish water with an appropriate TDS value allowing to use it for RO desalination membranes is available in West Bank.
- Since the RO desalination systems are considered to consume the lowest amount of energy, RO systems are very appropriate to be operated by solar electric power systems represented in PV.
- Palestine enjoys a high solar energy potential amounting in average to 5.4 kWh/m²-day, therefore it is appropriate to exploit this energy in brackish water desalination using RO membranes.
- This study has shown that 1m³ of permeate water produced from brackish water with a TDS 2681mg/L, requires 2.3 kWh which is represented at $G_{av}=5.4$ kWh/m²-day approximately in 450 W_p PV cells.
- The economic analysis has shown that the cost of 1m³ of permeate water produced from brackish water with a TDS 2681mg/L is 3.17\$ with battery, and 2.33\$ without battery.
- Battery bank represent 23% from capital cost of Az Zubeidat project and 26.5% from all project cost during the total life time (20 years).
- For remote area having only such brackish water as Az Zubeidat village who depends only on potable water delivery trucks to secure its needs of drinking water, the annual saving would be 17740\$ when using RO brackish water desalination system powered by PV, for a daily capacity of drink water amounting to 10m³/day.

- Environmental analysis shows that Az Zubaidat system preserves the environment of production 4195 kg of CO₂ per year.
- Az Zubaidat project produce brine solution contains about 11274 kg/year.

8.2 Recommendation

- Based on the above obtained investigation results, it is recommended to consider seriously the PV powered RO desalination system for rural villages having only brackish water.
- Study the possibility of increasing the recovery in order to increase the productivity of the system.
- Provide the public places such as schools and health clinics in remote villages that have only BW with such systems to ensure high productivity and reliability of these systems.
- Studying ways to exploit the brine as salt food or chemical fertilizer or any other usefulness.
- Operation these systems without using storage batteries to reducing the cost of the system and thus reducing the cost of one m³ of product water.

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Appendices

Appendix A1: Table of interest at $i = 6\%$

Appendix A2: Table of interest at $i = 20\%$

Appendix A1

Table of interest $i=6\%$

6% TABLE 11 Discrete Cash Flow: Compound Interest Factors 6%								
n	Single Payments		Uniform Series Payments				Arithmetic Gradients	
	Compound Amount F/P	Present Worth P/F	Sinking Fund A/F	Compound Amount F/A	Capital Recovery A/P	Present Worth P/A	Gradient Present Worth P/G	Gradient Uniform Series A/G
1	1.0600	0.9434	1.00000	1.0000	1.06000	0.9434		
2	1.1236	0.8900	0.48544	2.0600	0.54544	1.8334	0.8900	0.4854
3	1.1910	0.8396	0.31411	3.1836	0.37411	2.6730	2.5692	0.9612
4	1.2625	0.7921	0.22859	4.3746	0.28859	3.4651	4.9455	1.4272
5	1.3382	0.7473	0.17740	5.6371	0.23740	4.2124	7.9345	1.8836
6	1.4185	0.7050	0.14336	6.9753	0.20336	4.9173	11.4594	2.3304
7	1.5036	0.6651	0.11914	8.3938	0.17914	5.5824	15.4497	2.7676
8	1.5938	0.6274	0.10104	9.8975	0.16104	6.2098	19.8416	3.1952
9	1.6895	0.5919	0.08702	11.4913	0.14702	6.8017	24.5768	3.6133
10	1.7908	0.5584	0.07587	13.1808	0.13587	7.3601	29.6023	4.0220
11	1.8983	0.5268	0.06679	14.9716	0.12679	7.8869	34.8702	4.4213
12	2.0122	0.4970	0.05928	16.8699	0.11928	8.3838	40.3369	4.8113
13	2.1329	0.4688	0.05296	18.8821	0.11296	8.8527	45.9629	5.1920
14	2.2609	0.4423	0.04758	21.0151	0.10758	9.2950	51.7128	5.5635
15	2.3966	0.4173	0.04296	23.2760	0.10296	9.7122	57.5546	5.9260
16	2.5404	0.3936	0.03895	25.6725	0.09895	10.1059	63.4592	6.2794
17	2.6928	0.3714	0.03544	28.2129	0.09544	10.4773	69.4011	6.6240
18	2.8543	0.3503	0.03236	30.9057	0.09236	10.8276	75.3569	6.9597
19	3.0256	0.3305	0.02962	33.7600	0.08962	11.1581	81.3062	7.2867
20	3.2071	0.3118	0.02718	36.7856	0.08718	11.4699	87.2304	7.6051
21	3.3996	0.2942	0.02500	39.9927	0.08500	11.7641	93.1136	7.9151
22	3.6035	0.2775	0.02305	43.3923	0.08305	12.0416	98.9412	8.2166
23	3.8197	0.2618	0.02128	46.9958	0.08128	12.3034	104.7007	8.5099
24	4.0489	0.2470	0.01968	50.8156	0.07968	12.5504	110.3812	8.7951
25	4.2919	0.2330	0.01823	54.8645	0.07823	12.7834	115.9732	9.0722
26	4.5494	0.2198	0.01690	59.1564	0.07690	13.0032	121.4684	9.3414
27	4.8223	0.2074	0.01570	63.7058	0.07570	13.2105	126.8600	9.6029
28	5.1117	0.1956	0.01459	68.5281	0.07459	13.4062	132.1420	9.8568
29	5.4184	0.1846	0.01358	73.6398	0.07358	13.5907	137.3096	10.1032
30	5.7435	0.1741	0.01265	79.0582	0.07265	13.7648	142.3588	10.3422
31	6.0881	0.1643	0.01179	84.8017	0.07179	13.9291	147.2864	10.5740
32	6.4534	0.1550	0.01100	90.8898	0.07100	14.0840	152.0901	10.7988
33	6.8406	0.1462	0.01027	97.3432	0.07027	14.2302	156.7681	11.0166
34	7.2510	0.1379	0.00960	104.1838	0.06960	14.3681	161.3192	11.2276
35	7.6861	0.1301	0.00897	111.4348	0.06897	14.4982	165.7427	11.4319
40	10.2857	0.0972	0.00646	154.7620	0.06646	15.0463	185.9568	12.3590
45	13.7646	0.0727	0.00470	212.7435	0.06470	15.4558	203.1096	13.1413
50	18.4202	0.0543	0.00344	290.3359	0.06344	15.7619	217.4574	13.7964
55	24.6503	0.0406	0.00254	394.1720	0.06254	15.9905	229.3222	14.3411
60	32.9877	0.0303	0.00188	533.1282	0.06188	16.1614	239.0428	14.7909
65	44.1450	0.0227	0.00139	719.0829	0.06139	16.2891	246.9450	15.1601
70	59.0759	0.0169	0.00103	967.9322	0.06103	16.3845	253.3271	15.4613
75	79.0569	0.0126	0.00077	1300.95	0.06077	16.4558	258.4527	15.7058
80	105.7960	0.0095	0.00057	1746.60	0.06057	16.5091	262.5493	15.9033
85	141.5789	0.0071	0.00043	2342.98	0.06043	16.5489	265.8096	16.0620
90	189.4645	0.0053	0.00032	3141.08	0.06032	16.5787	268.3946	16.1891
95	253.5463	0.0039	0.00024	4209.10	0.06024	16.6009	270.4375	16.2905
96	268.7590	0.0037	0.00022	4462.65	0.06022	16.6047	270.7909	16.3081
98	301.9776	0.0033	0.00020	5016.29	0.06020	16.6115	271.4491	16.3411
100	339.3021	0.0029	0.00018	5638.37	0.06018	16.6175	272.0471	16.3711

Appendix A2

Table of interest $i=20\%$

20%		TABLE 22 Discrete Cash Flow: Compound Interest Factors						20%
n	Single Payments		Uniform Series Payments				Arithmetic Gradients	
	Compound Amount F/P	Present Worth P/F	Sinking Fund A/F	Compound Amount F/A	Capital Recovery A/P	Present Worth P/A	Gradient Present Worth P/G	Gradient Uniform Series A/G
1	1.2000	0.8333	1.00000	1.0000	1.20000	0.8333		
2	1.4400	0.6944	0.45455	2.2000	0.65455	1.5278	0.6944	0.4545
3	1.7280	0.5787	0.27473	3.6400	0.47473	2.1065	1.8519	0.8791
4	2.0736	0.4823	0.18629	5.3680	0.38629	2.5887	3.2986	1.2742
5	2.4883	0.4019	0.13438	7.4416	0.33438	2.9906	4.9061	1.6405
6	2.9860	0.3349	0.10071	9.9299	0.30071	3.3255	6.5806	1.9788
7	3.5832	0.2791	0.07742	12.9159	0.27742	3.6046	8.2551	2.2902
8	4.2998	0.2326	0.06061	16.4991	0.26061	3.8372	9.8831	2.5756
9	5.1598	0.1938	0.04808	20.7989	0.24808	4.0310	11.4335	2.8364
10	6.1917	0.1615	0.03852	25.9587	0.23852	4.1925	12.8871	3.0739
11	7.4301	0.1346	0.03110	32.1504	0.23110	4.3271	14.2330	3.2893
12	8.9161	0.1122	0.02526	39.5805	0.22526	4.4392	15.4667	3.4841
13	10.6993	0.0935	0.02062	48.4966	0.22062	4.5327	16.5883	3.6597
14	12.8392	0.0779	0.01689	59.1959	0.21689	4.6106	17.6008	3.8175
15	15.4070	0.0649	0.01388	72.0351	0.21388	4.6755	18.5095	3.9588
16	18.4884	0.0541	0.01144	87.4421	0.21144	4.7296	19.3208	4.0851
17	22.1861	0.0451	0.00944	105.9306	0.20944	4.7746	20.0419	4.1976
18	26.6233	0.0376	0.00781	128.1167	0.20781	4.8122	20.6805	4.2975
19	31.9480	0.0313	0.00646	154.7400	0.20646	4.8435	21.2439	4.3861
20	38.3376	0.0261	0.00536	186.6880	0.20536	4.8696	21.7395	4.4643
22	55.2061	0.0181	0.00369	271.0307	0.20369	4.9094	22.5546	4.5941
24	79.4968	0.0126	0.00255	392.4842	0.20255	4.9371	23.1760	4.6943
26	114.4755	0.0087	0.00176	567.3773	0.20176	4.9563	23.6460	4.7709
28	164.8447	0.0061	0.00122	819.2233	0.20122	4.9697	23.9991	4.8291
30	237.3763	0.0042	0.00085	1181.88	0.20085	4.9789	24.2628	4.8731
32	341.8219	0.0029	0.00059	1704.11	0.20059	4.9854	24.4588	4.9061
34	492.2235	0.0020	0.00041	2456.12	0.20041	4.9898	24.6038	4.9308
35	590.6682	0.0017	0.00034	2948.34	0.20034	4.9915	24.6614	4.9406
36	708.8019	0.0014	0.00028	3539.01	0.20028	4.9929	24.7108	4.9491
38	1020.67	0.0010	0.00020	5098.37	0.20020	4.9951	24.7894	4.9627
40	1469.77	0.0007	0.00014	7343.86	0.20014	4.9966	24.8469	4.9728
45	3657.26	0.0003	0.00005	18281	0.20005	4.9986	24.9316	4.9877
50	9100.44	0.0001	0.00002	45497	0.20002	4.9995	24.9698	4.9945
55	22645		0.00001		0.20001	4.9998	24.9868	4.9976

الملخص

تحلية المياه المالحة باستخدام تقنية التناضح العكسي والتي تعمل بالطاقة الشمسية باستخدام الخلايا الكهروضوئية تعتبر واحدة من أكثر التكنولوجيات الواعدة في إنتاج المياه الصالحة للشرب. يمكن لهذه النظم الصغيرة التي تقع في المناطق النائية كسر الاعتماد على تحلية المياه التقليدية بواسطة الوقود الأحفوري، والحد من تكاليف الحصول على المياه الصالحة للشرب، وتحسين الاستدامة البيئية.

تتناقش هذه الأطروحة الطاقة اللازمة، والجوانب الفنية والاقتصادية، والتحليل البيئي لأول نظام تحلية في الضفة الغربية . تم بناء هذا النظام في قرية الزبيدات في وادي الأردن لاثبات امكانية استخدام الطاقة الشمسية في تحلية المياه وتزويد السكان بالمياه الصالحة للشرب.

هذا النظام ينتج 10 م³ من المياه الصالحة للشرب يوميا بتحلية مياه مالحة يبلغ اجمالي المواد المذابة فيها 2680 ملغ/ لتر، باستخدام تكنولوجيا التناضح العكسي التي تعمل بخلايا شمسية قدرتها 5.2 كيلو واط.

وبين تحليل الطاقة أن 1 م³ من المياه الصالحة للشرب المنتجة يحتاج 2.3 كيلوواط ساعة من الطاقة الكهربائية والتي تتمثل بحوالي 450 واط من الخلايا الشمسية.

وبين التحليل الاقتصادي أن تكلفة 1 م³ من المياه الصالحة للشرب التي ينتجها هذا النظام هو 3.17 دولار عند استخدام البطاريات و2.33 دولار دون استخدام البطاريات هذه النتيجة هي معقولة جدا مقارنة مع 5.07 دولار تكلفة المياه الصالحة للشرب من الشاحنات، وهذا النظام يوفر 17740 دولار سنويا.

وبين التحليل البيئي أن استخدام مثل هذه النظم الصغيرة يحافظ على البيئة من إنتاج 4195 كجم من غاز CO₂ سنويا.