Solar Thermal Desalination: A Sustainable Alternative for Sultanate of Oman

Parimal S. Bhambare *‡, M. C. Majumder **, Sudhir C. V. ***

*Department of Mechanical and Industrial Engineering, Caledonian College of Engineering, Muscat, Sultanate of Oman

**Department Mechanical Engineering, National Institute of Technology, Durgapur

*** Department of Mechanical and Industrial Engineering, Caledonian College of Engineering, Muscat, Sultanate of Oman

(parimal.bhambare@gmail.com, manik_rec@yahoo.com, sudhir@caledonian.edu.om)

‡ Corresponding Author; Parimal S. Bhambare, Department of Mechanical and Industrial Engineering, Caledonian College of Engineering, PO Box 2322, CPO Seeb 111, Muscat, Sultanate of Oman, Tel: +968 24536165,

Fax: +968 24535675, parimal.bhambare@gmail.com

Received: 04.11.2017 Accepted:14.02.2018

Abstract- Desalination plays a critical role in filling the gap between freshwater demand and availability in water-scarce Sultanate of Oman since 1976. Installed desalination capacity in the country has almost increased by 60 times that in 1976 with increasing fresh water demand. Even though desalination share is increasing, 80-85% of freshwater demand today is still satisfied with groundwater and natural sources. This is leading to increased soil salinity in recent years affecting the crop production. All the planned and installed desalination plants in the country use conventional fuels for their operation. None of the plants are based on any form of renewable energy source. Consumption of fossil fuels for the operation of these plants is increasing at an average rate of 3-5% affecting the net export for the country. Sultanate of Oman is considered to be one of the most suitable destinations for solar energy applications and solar energy can play a vital and sustainable role in meeting the gap between the demand and supply of fresh water using solar thermal desalination. This paper emphasizes on addressing this aspect for the country. An overview of present desalination status and fresh water demand, fuel requirements, solar energy availability, thermal desalination technologies and solar thermal technologies has been presented in the paper. Conventional thermal desalination technologies and solar thermal technologies have been compared for same capacity on the scale of 1 to 5 for various factors in the context of Sultanate of Oman. Few of the challenges and barriers in the implementation of solar thermal desalination in the country are also discussed in the paper. Fixed focus type Scheffler dish reflectors (SDR) are suggested as one of the best suitable option to be coupled with multi-effect desalination technology for small to medium capacity decentralized type plants. Parabolic trough collectors (PTC) coupled with Combined Cycle Gas Turbine (CCGT) or Open Cycle Gas Turbine (OCGT) plants would be a feasible solution for higher capacity desalination plants.
Keywords Thermal desalination; Scheffler dish reflector (SDR); Multi Effect Desalination (MED); CCGT; OCGT; PTC.

1. Introduction

Sultanate of Oman is the second largest country after Saudi Arabia located at the southeast tip of Arabian Peninsula lying on the Arabian sea and sea of Oman with an approximate area of 3,09,500 sq. km. It is located within an arid and semi-arid region with an average annual rainfall between 50 - 100 mm over the country varying from 20 mm in the internal dessert to 300 mm in mountains. Out of this 80% is lost to evaporation leaving only 20% as surface runoffs or groundwater direct infiltration [62]. Availability of fresh water is always a challenge and since ancient times its demand is satisfied through several conventional and non-conventional resources. Conventional water resources in Sultanate include surface and groundwater resources. Surface resources include natural springs, afalaj, ghail and wadis [1] while groundwater resources mainly include wells spread all over Sultanate. As shown in Fig. 1, almost 80% of the freshwater demand as on today also is satisfied by groundwater as compared to other resources. Moreover, fresh water is available only in the northern and southern end of the country while water in other regions is brackish or saline [2]. As per the statistics presented by Ministry of Regional Municipalities and Water Resources at 11th Gulf Water Conference [2], fresh water demand has exceeded by 31% over the renewable sources in 2014 which was met through desalination, treated waste water and recharge dams. The data published by World Resource Institute in 2011 for Middle East Countries shows that water consumption in the country is almost 181% [63] of the available renewable resources. This could be referred from Fig. 2. Apart from this, over mining of groundwater for different domestic and industrial applications is not only causing seawater intrusion and salinization of soils but also ground water levels are falling down rapidly in different regions of the country. Almost 40% of the total area of Oman is affected by salinity [3] which could be seen from the salinity map of the country shown in Fig. 4. At the same time, water supply from wells have shown a continuous decline and contributed only 15-20% of the total demand in 2012 [4]. This could be seen in Fig. 6 (a). Due to this government has imposed restrictions on the boring of new wells in the country for the protection of available water resources to support national policy for recharge of aquifers [62].

A report published by the International Water Management Institute (IWMI) in 2007 has classified Oman as one of the countries experiencing 'physical water scarcity' [6]. Moreover, another study has also shown that the freshwater resources in the country could provide only about 500 m^3 per person per year [7].

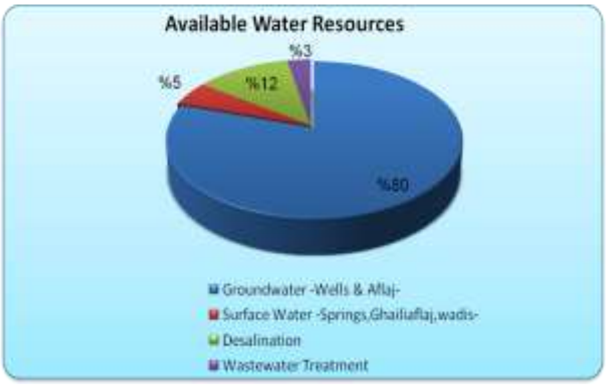


Fig. 1: Available water resources in Oman [2]

As a result, as shown in Fig. 5, according to the statistics for the availability of freshwater resources available across the globe, published by UNESCO in 2015, Oman is categorized among regions where freshwater resources are 'absolutely scarce' [8].

Fig. 2: Water used as a percentage of renewable resources [63]

Increasing population, economic and industrial development, urbanization and profound proposed future developments has always demanded reliable uninterrupted electricity and water supply in the country as reflected in Fig. 3.

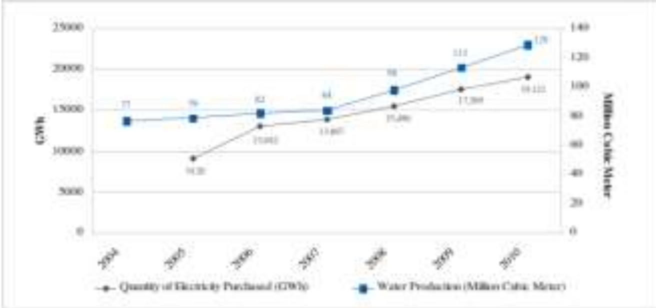


Fig. 3: Growth in Electricity and Water Consumption in Oman [3]

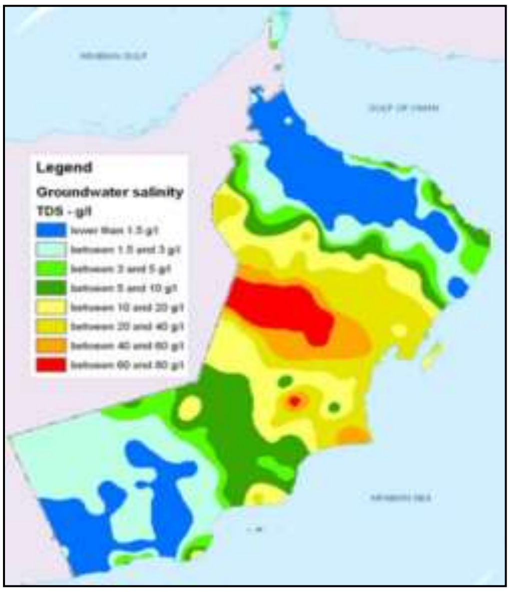


Fig. 4: Salinity map of groundwater for Oman [2]

As per the published data from OPWP the peak demand for water has increased from 86 million m^3 per year in 2006 [9] to 425.77 million m^3 per year in 2016 [5] (for 426.831 million m^3 per year installed capacity in 2016) at an average growth rate of 6-8% annually. According to OPWP's forecast in 2017 the peak demand with the margin for fresh potable water is expected to rise at an average rate of 5-9% per year to 815.26 million m^3 per year in 2023 [5].

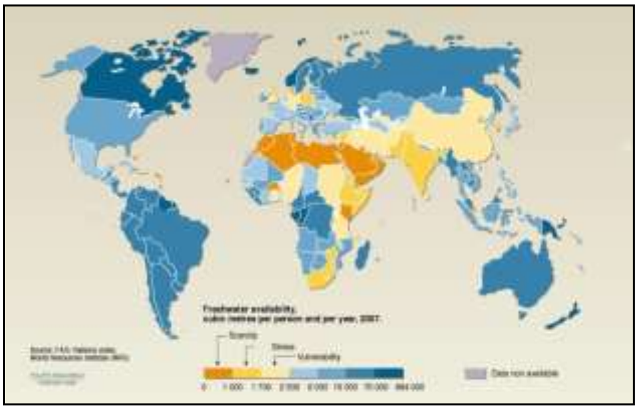


Fig. 5: Availability of renewable water resources [8]

Table 1. Operating desalination plants in Oman, 2010 [10]

Sr. No.	Plant Location	Capacity		Technology used	Number of Units	Year of Commissioning
		MGPD	m³/day			
1.	Abu Mudhabi	0.055	250	RO	2	1985-2012
2.	Adam	0.372	1691	RO	3	1997-2009
3.	Al Ghubrah -1	42	190909	MSF	7	1976-2001
4.	Al Ghubrah -2	5	22727	RO	24	2010
5.	Al Najdah- 1	0.022	100	RO	1	2008
6.	Al Najdah- 2	0.044	200	FO	1	2012
7.	Alkahal	0.017	77	RO	1	2006
8.	AlKhalouf	0.022	100	FO	1	2010
9.	Alkhiran	0.033	150	RO	1	2003
10.	AlKhulouf	0.022	100	RO	1	2007
11.	Alkhuwaiymah	0.088	400	RO	2	2001-2012
12.	Allakbi	0.022	100	RO	1	2005
13.	Alsa’adanat	0.033	150	RO	2	1985-2001
14.	Alsail & Al Ramlah	0.022	100	RO	1	2004
15.	Alsifah	0.022	100	RO	1	2003
16.	Alzahiya	0.022	100	RO	1	2001
17.	Bamah	0.132	600	RO	2	2002-2012
18.	Barka ACWA	20	90909	MSF	3	2003
19.	Barka SMN	26	118182	RO	1	2009
20.	Dibba	0.88	4000	RO	2	2008-2012
21.	Eshairgah	0.022	100	RO	1	1995
22.	Film	0.055	250	RO	1	2012
23.	Fins	0.022	100	RO	1	2002
24.	Haima	0.132	600	RO	1	1995-2009
25.	Hamra’a Al dorou’	0.264	1200	RO	1	2008
26.	Hijj	0.396	1800	RO	2	1995-2012
27.	Hitam	0.044	200	RO	1	2012
28.	Khumkham	0.022	100	RO	1	1995
29.	Kumzar	0.077	350	RO	2	1996-2012
30.	Lima	0.066	300	RO + ED	2	1983-2008
31.	Madraka	0.11	500	RO	2	2007-2010
32.	Musairah	0.726	3300	RO	3	2001-2008
33.	Qarn Alalam	0.044	200	RO	1	2001-2012
34.	Qurayat	1.5	6818	RO	2	2010-2012
35.	Ras Alhad	0.11	500	RO	1	2006
36.	Sarab	0.066	300	RO	1	2012
37.	Sheesa	0.044	200	RO	3	2008
38.	Sohar	33	150000	MSF	4	2007
39.	Soqrah	0.066	300	RO	2	1998-2012
40.	Sur	16.7	75909	RO	1	2010
41.	Zahar	0.121	550	RO	3	1985-2010
	Total	**148.40**	**674522.7**			

This unyielding pressure on water resources has forced Oman, like other GCC countries, to satisfy the deficit in supply and demand through desalination plants that utilize seawater and fulfill the fresh water requirements. The first desalination plant in Oman has been installed in 1976 at Al Ghubra and Massira with Multi-Stage Flash technology

Table 2. Desalination status for Oman, current and future (OPWP 7 YEAR STATEMENT 2015-2021 and 2017-23) [5][11]

Zone/Region	Installed Capacity, m^3/day	Planned Capacity, m3/day
Interconnected Zone	**Ghubra:** 140,200 m^3/day 05 MSF units, OCGT (Open cycle Gas Turbine)	
	Barka I: 91,200 m^3/day, MSF, Natural gas, CCGT (Combined Cycle Gas Turbine)	**Barka I:** 102000 m^3/day (Additional capacity from May 2014 to Jan 2016) using RO
	Barka II: 120,000 m^3/day using RO, CCGT	**Barka III/IV:** 281,000 m^3/day from 2018 RO
	Sohar I: 150,000 m^3/day, MSF, CCGT	**Sohar II/III:** 251,000 m^3/day in 2018 RO
	Muscat City/ Ghubra II: 191,000 m^3/day, RO from August 2015	**Qurayyat:** 200,000 m^3/day from May 2017
	Additional capacity: 300,000 m^3/day planned to be operational by 2021 (site under evaluation)	
Sharqiyah zone	**Sharqiyah desalination plant:** 83,000 m^3/day, RO	**New Plant:** 55,000 m^3/day in 2021
	Sur desalination Plant: 48,000 m^3/day, RO from 2016	
Dhofar	**Salalah desalination plant:** 68,190 m^3/day RO from 2013	**New plant (Taqa):** 80,000 – 100,000 m^3/day from 2019
Ad Duqm and Musandam	**Duqm:** 6,000 + 6,000 m^3/day from 2015	**Duqm IWP:** 55,000 – 60,000 m^3/day from 2019 RO
	Musandam: 450 m^3/day (Kumzar), 3,500 m^3/day (03 plants)	**New Plant (Khasab):** 13,000 m^3/day planned 2017 RO

MSF) producing 18930 m^3/day and 126 m^3/day of desalinated water respectively.

For satisfying the increasing demand for fresh water, different desalination plants have been installed in the country. Table 1 summarizes 41 installations with single or multiple units in the country in 2012, based on the capacity, the technology used, and commissioning year for the plant. Most of the plants installed are combined with power generation unit and uses the electrical power and the waste heat available from the power plant for its operation. These plants operate on conventional fuel which is primarily natural gas or fuel oil. Availability of electrical power from CCGT plants, advancements in the RO technology and economic advantage of Reverse Osmosis (RO) systems with combined water and power generation plant led to the exhaustive use of this technology for almost 75-80% of installed plants in the country. The total installed desalination capacity in the country has been increased from 19.5 thousand m^3/day in 1976 to 1169.4 thousand m^3/day (426.83 million m^3/year) in 2016 [5], which is almost 60 times the installed capacity in 1976. Table 2 gives the details of the currently installed and planned capacity of desalination in Oman in 2016. From Fig. 6(a) and Table 2 it could be seen that almost 80 - 85% of the installed desalination plants are combined with power plants. Standalone and rural installations are very few in Oman.

2. Natural Gas and Oil Consumption for Electricity and Water Production

Like the other GCC countries in the region, Oman is the fastest developing country and tops fifth largest economy in the region. Oil and gas till date remain as the sole contributors for the economic development of the country. These sectors contributed to 47.6% of the country's GDP in 2010 and 81% of the country's revenue in 2006.

In line with the population growth and industrialization, domestic consumption of oil has been doubled while that of natural gas consumption has been tripled in the last decade as shown in Fig. 7. Electrical sector of the country heavily depends on natural gas which contributes to almost 97.5% of the electricity generation as shown in Fig. 7(b). Almost all the desalination plants in the country are RO based and operated together with natural gas based power plants in cogeneration. Fig. 8 shows the comparison of total natural gas consumption with consumption for water and power production. Almost 19.5% of the total consumption is towards the water and power generation for the country in 2011 as shown in Fig. 7(a). OPWP's projections for 2017-23 shows that natural gas consumption is expected to increase at an average rate of 3% per year from 19.5 million Sm^3 per day in 2016 to 23.2 million Sm^3 per day in 2023 with a peak demand to rise at an average rate of 1% per year from 28.9 million Sm^3 per day to 31.6 million Sm^3 per day in 2023. Moreover, it has been estimated that the production of

1000 m^3 per day of freshwater requires 10,000 tons of oil per year [61]. This will be highly significant with increasing demand for fresh water bridged by desalination.

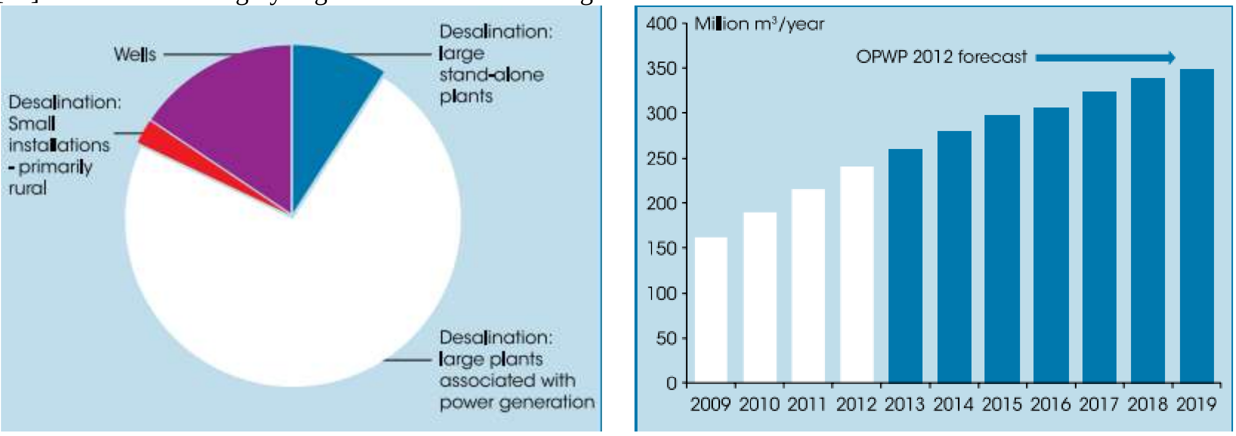


Fig. 6 (a) Water supply resources in 2013 (b) Water production actual and forecast [4]

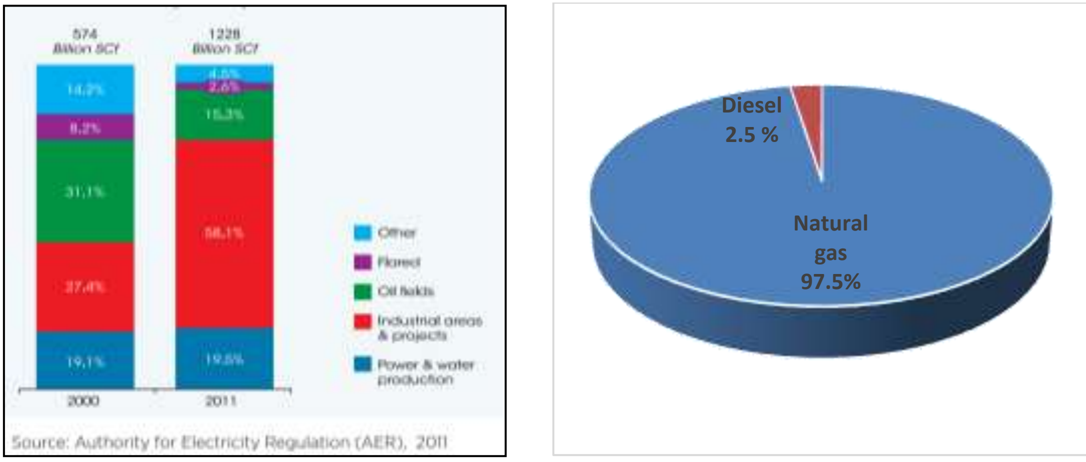


Fig. 7: (a) Natural gas use 2000 & 2011 comparison (b) Electricity generation by fuel in 2011 [4]

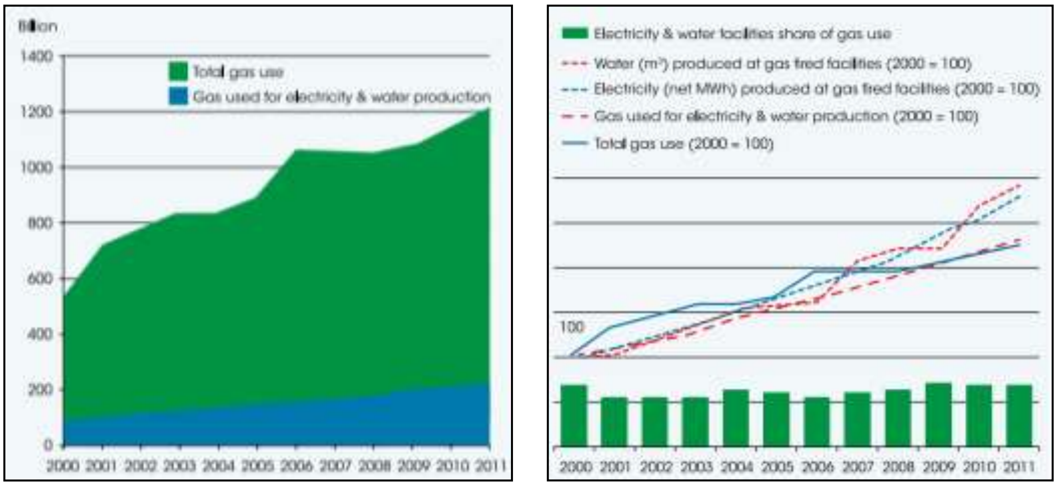


Fig. 8: (a) Total gas use 2000-2011 (b) Gas use for power and water production [4]

Oil and natural gas being the non-renewable sources, other GCC countries have already set their targets for diversifying their energy resources to renewable type, for example, Qatar aims to generate 20% of its energy from renewable by 2024. Sultan Qaboos bin Said's "Vision 2020" policy has now established a goal of producing 10 percent of Oman's total electricity and water (implied with combined power and desalination plants in the Sultanate) requirements from renewable energy sources by 2020 [12].

Wind and solar energy sources are identified as the most promising renewable sources for the Sultanate of Oman through different research studies. Being a tropical country, solar energy is considered as one of the best renewable resources for the country. This paper focuses on the prospectus of solar thermal energy for the country for desalination.

3. Solar Energy Potential for Sultanate of Oman

Oman being a tropical country with high ratio of sky clearness index for almost 342 days/year [3] receives higher solar insolation throughout the year and is considered to be one of the best destinations in the world for tapping the solar energy. Majority of the land receives almost 2300 – 3500 W/m^2/day in January and 5500 – 7300 W/m^2/day in July as shown in Fig. 10. There are 25 meteorological stations set up in Oman. Fig. 9 shows the global average daily sunshine hours and solar radiation values for these 25 stations. It could be seen that the average daily sunshine hours and insolation varies from, 8 hrs/day at Sur to 10.2 hrs/day at Buraimi and 4 kWh/m^2/day at Sur to 6.1 at Marmul kWh/m^2/day. Also the average daily global radiation and sunshine hrs at these destinations is above 5 kW/m^2/day and 8.5 hrs/day respectively. Marmul is considered to be the best destination amongst all, receiving the highest global average daily solar radiation. Furthermore, the sky clearness index at nearly all the destinations except a few like Salalah and Sur due to summer rain and fog, is also very high throughout the year. Addition to this as shown in Fig. 12 the World Map GHI shows that the long term average of annual sum and daily sum of global horizontal irradiation for Oman is between 2200 – 2700 kWh/m^2 and 6 – 6.75 kWh/m^2 respectively. Furthermore, Fig. 10 also gives the comparison between July and January for the global solar radiation received in the country. As expected the average global solar radiation received is above 6000 W/m^2/day for July as compared to 3000 W/m^2/day in January. Also, the average temperature for the country is 28.76ºC while the average highest temperature reaches above 46ºC at different locations. Locally at the interior in dessert temperature could even reach above 54ºC [73] also in the month of June-July. Fig. 11 shows the average temperature for January and June for the country.

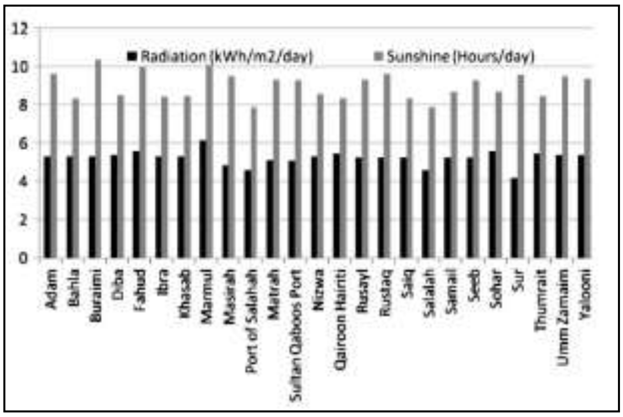


Fig. 9: Average yearly solar radiation and sunshine hours at 25 destinations in Oman[13]

4. Solar Photovoltaic System

Solar PV cells are used to convert sunlight directly into electrical energy using photovoltaic effect. Solar PV panels powering different domestic and commercial installation worldwide.

Several panels are connected together either in series or parallel combination to form a solar array to produce the desired power output at a specified voltage and current for an application. Traditionally solar cells are made up of silicon, which is a flat-plate type and generally the most efficient. These are used widely in all the large-scale commercial applications. Several small capacity pilot plants up to few hundred kW capacities have been installed at several locations in the country.

In general, solar photovoltaic systems have a lower efficiency that further reduces with increasing ambient temperature and excessive solar radiation conditions. Power output from the PV cells decreases as the cell temperature increases [71] [72] as can be seen in Fig. 13 below. It is observed that with every 1ºC rise in the cell temperature efficiency decreases by 0.5% [16]. The maximum temperature at different locations in Oman ranges between 45-50ºC in June-July while the average annual temperature is between 25-30ºC. The maximum and the average annual temperature at author's institute between Jan - Dec 2017 are recorded to be 46.5ºC and 28.8ºC respectively.

A study has been carried out on PV panels of 3.2 kW power output installed at author's institute to understand the PV panel temperature variation with ambient temperatures. The ambient and PV panels' temperatures are recorded for the month of May 2016. It shows that the average temperature of PV panel is always above that of the ambient by 15ºC to 35ºC. The maximum temperature has even reached to 81.28ºC at 11 am on 8th May 2017 even though ambient was at 41.67ºC. This shows clearly that the PV panel temperature is always above the ambient and with further increase in ambient temperatures may reach above 82^{0}C. This could be read out from Fig. 14.

Higher ambient temperatures also demands for extra cooling systems for the solar PV arrays to maintain them below the maximum allowable temperature for the desired output at extra cost. Also being dessert country dust accumulation on photovoltaic panels is very common in the country. Accumulation of dust on the PV panel reduces the output power from the system. It is reported that 10 mg/cm^2 of dust accumulated on the panel decreases the power output by almost 90% [17]. With both high ambient temperatures and dust contamination it is expected that for Oman, the efficiency of the PV systems is expected to reduce minimum by 10 % [1]. Additionally, coastal destinations like Muscat have average relative humidity above 57.03% as measured at author's institute between Jan – Dec 2017. Furthermore, few research studies shown that PV modules are degraded by ambient temperature and humidity; moreover these factors accelerate the degradation.

A study is conducted by Charabi and Gastil in 2013 [18] for analyzing the suitability of Oman for solar energy applications based on Aerosol Optical Depth (AOD) maps. AOD analysis shown that with dust and temperature consideration, only 9% of the total land is highly suitable for the solar energy utilization in the country. Considering 70%

as the area factor, the total electricity generation potential using 13.1 % efficient PV systems is 5811 GWh/year, while

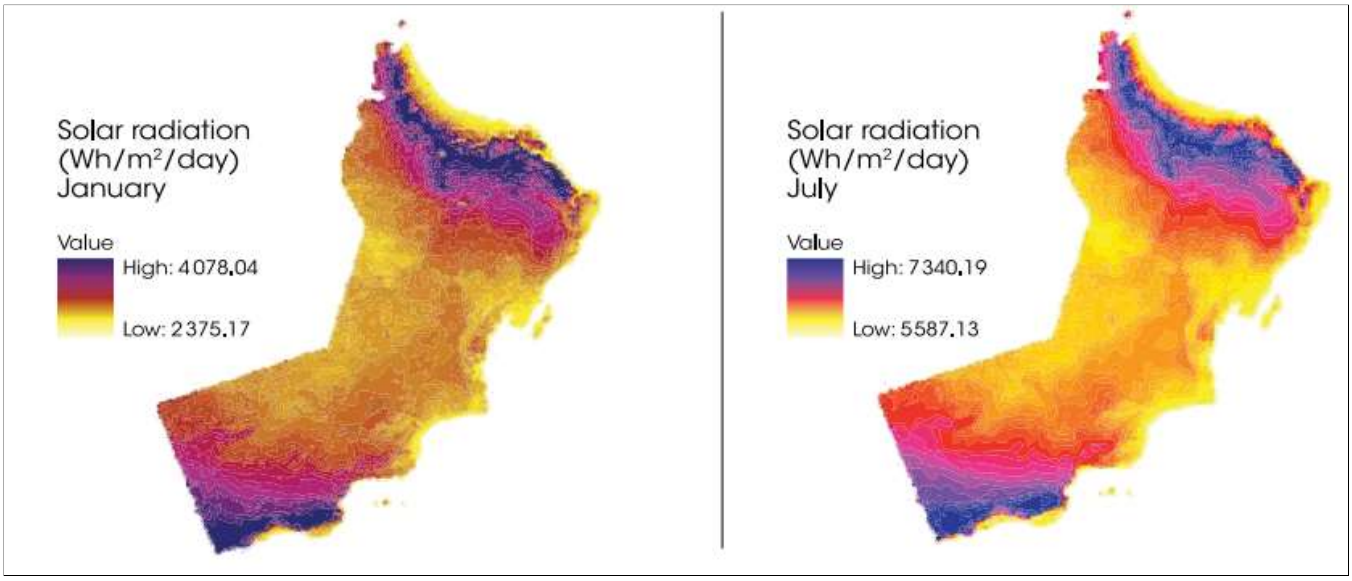


Fig. 10: Average solar radiation map for month of (a) January and (b) July [14]

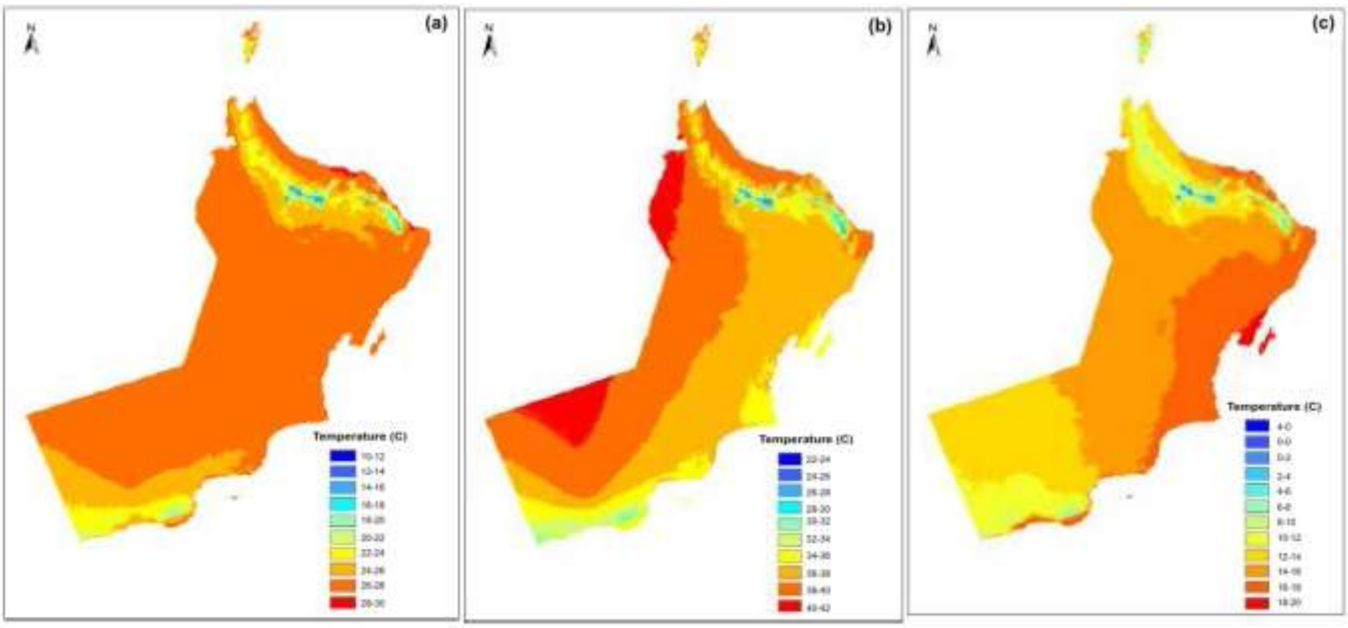


Fig. 11: Temperature patterns of Oman for the period 1961-1990, (a) Average annual (b) Average maximum for June and (c) Average minimum for January [15]

with 26.3% efficient concentrated PV system this could be raised to 11,667 GWh/year [18]. With marginal to moderate suitable areas included, the total suitability of the land can be raised to 36% [19]. This shows the limitations of PV system due to dust and temperature conditions in the country.

5. Solar Thermal System

Solar thermal systems are generally closed type systems that harness solar energy and convert it to the usable form. This system has following main components as shown in Fig. 15,

- Solar thermal collector
- Heat exchanger
- Heat utilizing system (application)
- Heat storage

Solar thermal collector, a special kind of heat exchanger absorbs the solar radiation, converts it into heat and transfers it to a working fluid (which is generally air, water, salt or oil). The working fluid will transfer this heat through a heat exchanger to the application or heat utilization system and the surplus amount is transferred to the storage for use at night time or cloudy days.

Different types of solar thermal collectors are used worldwide for absorbing the solar thermal energy. These are generally categorized into tracking and non-tracking type as shown in Table 3.

5.1 Flat plate collectors (FPC)

These are the simplest and stationary non-tracking type collectors used worldwide for supplying hot water or air (solar driers) at lower to medium temperatures for several industrial and domestic applications. These types of collectors use either flat or tubular type absorber which absorbs and transfer the heat energy to working fluid flowing through it. They are used as single unit to grid connected for satisfying small domestic to large industrial energy requirements. Fig. 16 (c) shows a schematic of solar flat collector.

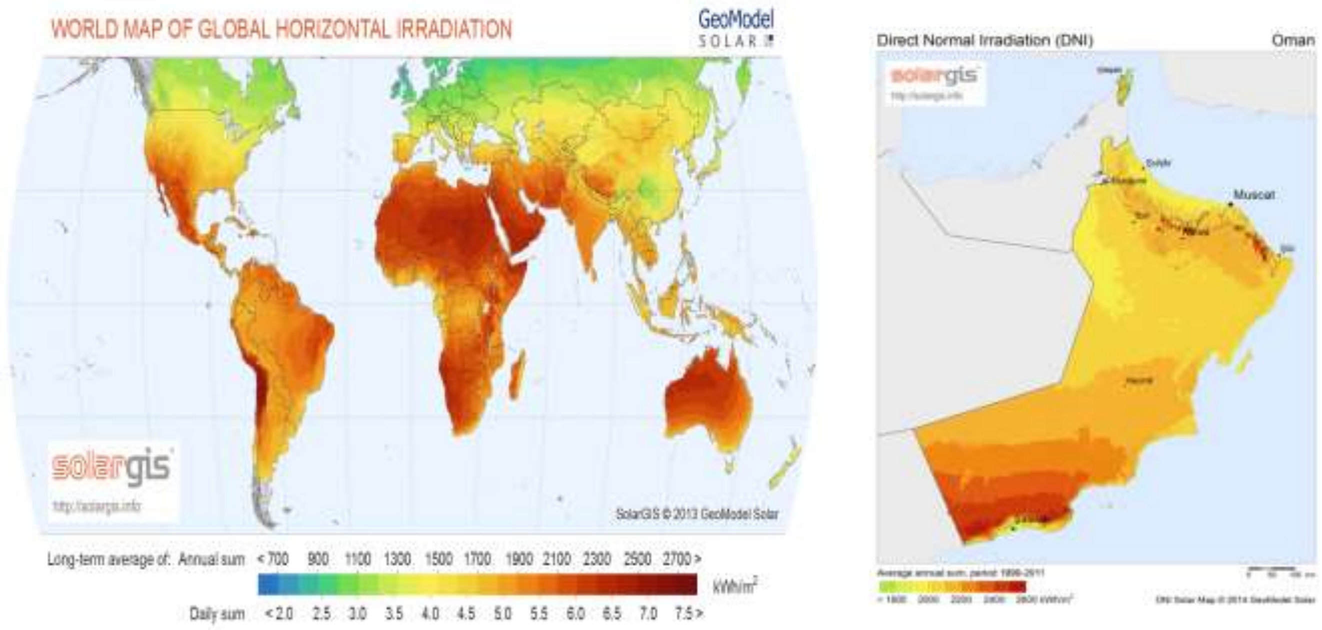


Fig. 12: a) World map of GHI Oman, b) DNI map of Oman source [64]

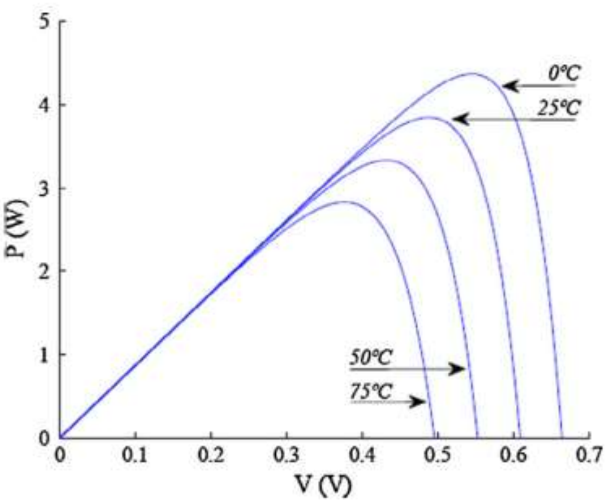


Fig. 13: Variation of PV output with temperature [16]

5.2 Linear Fresnel reflector (LFR)

Linear Fresnel collectors use several parallel flat or slightly curved mirrors mounted on the ground to concentrate sunlight onto one receiver which is several meters above the primary field. The mirrors used are much cheaper as compared to PTC also as these are mounted close to the ground, structural requirements are also lower. Fig. 16 (a) shows a representation of the LFR field.

Shading and blocking between adjacent reflectors, higher mirror surface per receiver, lower optical efficiency, requirement of secondary mirrors or high tower requirement for avoiding astigmatism due to focal line disturbances, more cosine losses as sunrays are not hitting the mirrors normally are few of the issues reported for LFR technologies [21][22]. Due to these issues the cost advantage for LFR technology needs to be compensated for the efficiency drawbacks.

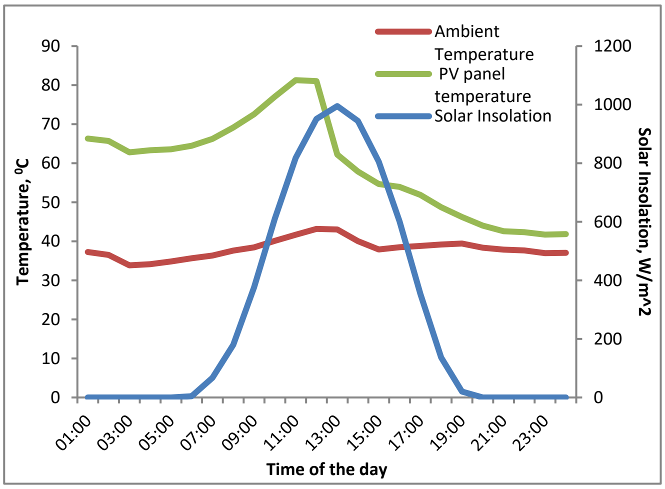


Fig. 14: Ambient temperature, PV panel temperature and Solar Insolation on 08/05/2017

Compact Linear Fresnel Reflector (CLFR) is newly developed technology that uses two receiver system that minimizes the shading and blocking problems along with requirement of higher tower height requirements. Most of the

LFR installations are pilot based and very few commercial installations are available worldwide.

5.3 Parabolic trough collector (PTC)

This is the most matured and advanced CSP technology accepted over the world. PTC can deliver temperatures from 60ºC to 300ºC with a concentration ratio of 15 - 45. As cited in different research titles PTC technology is the most accepted commercial CSP technology which accounts 85% of the total CSP installations worldwide in 2014 [23] for different commercial applications which include steam cooking to solar thermal power plants. PTC's are made from reflecting sheet bent in the shape of parabolic trough. A metal black tube covered with evacuated glass tube, to reduce convection losses, is placed along the focal line of the collector as shown in Fig. 16(b). When pointed towards sun, solar radiations incident on parabolic surface are concentrated on the receiver. Heat transfer fluid flowing inside the receiver absorbs and carries the heat to the application or thermal storage. Several of these collectors are installed in rows about a hundred meters long and the total solar field is composed of many such parallel rows.

Table 3: Different types of solar thermal collectors [20]

Motion	Collector type	Absorber type	Concentration ratio	Indicative temperature range (°C)
Stationary	Flat plate collector (FPC)	Flat	1	30–80
	Evacuated tube collector (ETC)	Flat	1	50–200
	Compound parabolic collector (CPC)	Tubular	1–5	60–240
Single-axis tracking			5–15	60–300
	Linear Fresnel reflector (LFR)	Tubular	10–40	60–250
	Parabolic trough collector (PTC)	Tubular	15–45	60–300
	Cylindrical trough collector (CTC)	Tubular	10–50	60–300
Two-axes tracking	Parabolic dish reflector (PDR)	Point	100–1000	100–500
	Heliostat field collector (HFC)	Point	100–1500	150–2000

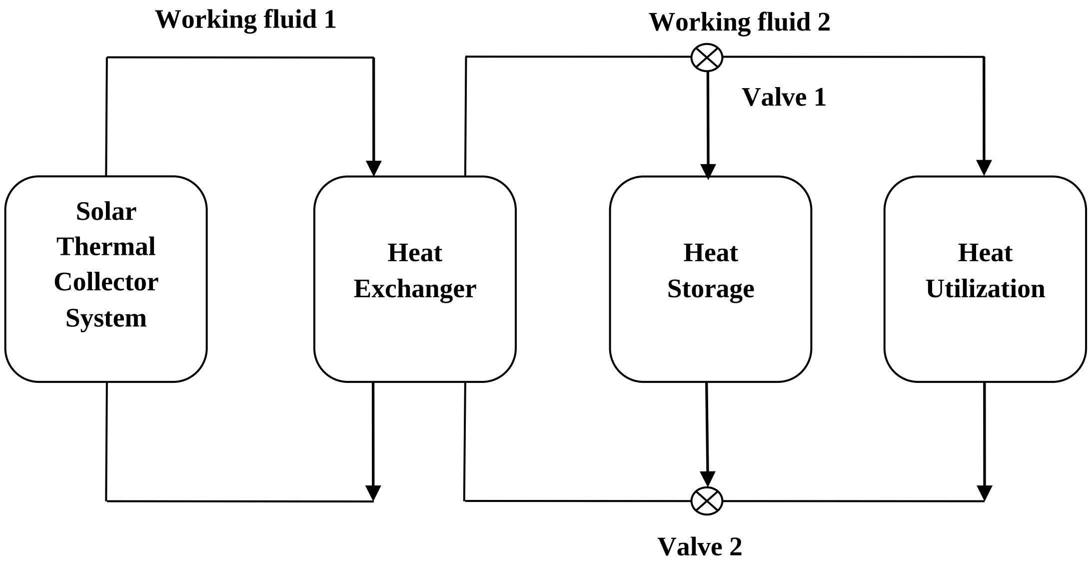


Fig. 15: Schematic of a solar thermal energy collection system

Miraah solar plant that uses enclosed PTC systems is under construction for steam production at Amal oil field for enhanced oil recovery in Oman. It is expected to be the world's largest solar field using enclosed PTC systems by its peak thermal capacity. The plant is expected to generate 1021 MWth producing almost 6000 tons of steam per day [24] saving almost 5.6 trillion British Thermal Units (BTU) of natural gas per year. Recently in February 2018, first four blocks of the plant (out of total 36) started delivering 660 tonnes of steam per day. The plant is expected to complete in 2019 [70].

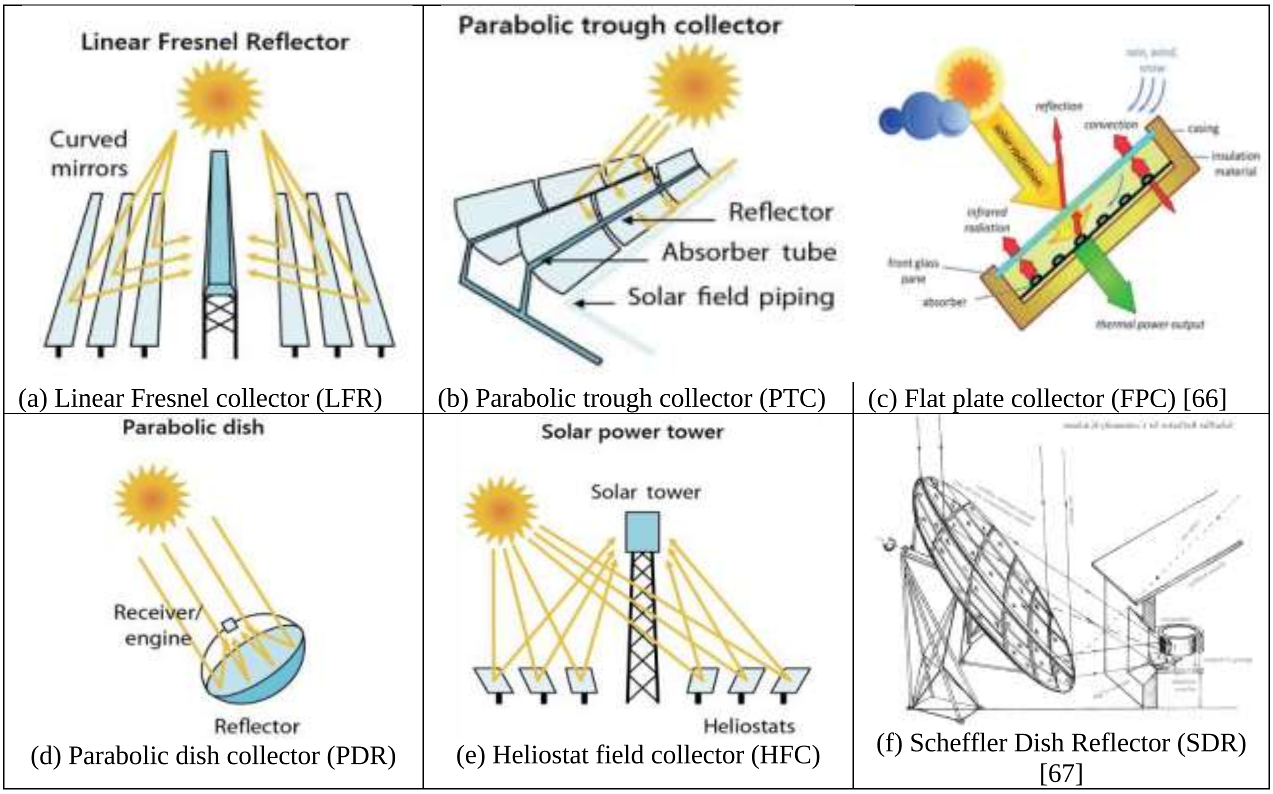
5.4 Parabolic Dish reflector (PDR)

A parabolic dish reflector is a point-focus type collector that tracks the sun continuously in two axes, concentrating solar energy onto a receiver located at the focal point of the dish as shown in Fig. 16(d). The dish structure must track fully the sun to reflect the beam into the thermal receiver. The receiver absorbs the radiant solar energy, converting it into thermal energy in a circulating fluid. The thermal energy can then either be directly utilized for application, or it can be transported through pipes to a central power-conversion or storage system. Parabolic-dish systems can achieve temperatures in excess of 1500ºC. Being the point focus collector that uses two axes tracking and concentration ratios in the range of 600-2000, PDR is the most efficient CSP technologies for thermal energy absorption and power conversion systems.

Higher cost, accurate tracking requirements, limitations on size due to structural requirements leads to lower energy collections per dish, more land requirement, requirement of skilled labor, piping layout along-with pumping requirements and thermal losses in the system are few of the issues with PDR. PDR technologies are generally applied for high temperature applications including metallurgical and power generation.

Table 4: Suitability of solar collectors for thermal desalination for same capacity – Oman (on scale of 1 to 5: 1 – Low, 5 – High)[25][26][27][28][29][30]

Collector type	Temperature range, °C	Ease of Installation	Equipment cost	Cleaning / operational requirement	Maintenance requirement	Land requirement	Skilled labour requirement	Suitable for	Remark
ETC / FPC	50-200	3	4-5	5	3-4	4-5	1-2	Lower capacity	
CPC	60-240	2-3	4	4-5	3	4-5	2-3	Lower capacity	
LFR	60-300	3	3-4	4	3-4	3	3-4	Lower capacity	Lower efficiency
PTC	60-250	4	3	3	3-4	3	4	Medium to large capacity	Higher efficiency
SDR (Scheffler)	100 - 250	2	2	2-3	2	2-3	1-2	Lower to Medium capacity	Fixed focus type, popularly used for low to medium temperature applications
PDR	100-500	3	4-5	2	3	1-2	5	Medium to large capacity	Used for medium to high temperature applications
HFC	150-2000	5	5	2-3	4-5	1-2	5	Very large capacity	Used for high temperature applications



(a) Linear Fresnel collector (LFR) (b) Parabolic trough collector (PTC) (c) Flat plate collector (FPC) [66]

(d) Parabolic dish collector (PDR) (e) Heliostat field collector (HFC) (f) Scheffler Dish Reflector (SDR) [67]

Fig. 16: Solar thermal collectors [65]

5.5 Heliostat field collector (HFC)

For extremely high inputs of radiant energy, a multiplicity of flat mirrors, or heliostats, using altazimuth mounts, can be used to reflect their incident direct solar radiation onto a common target as shown in Fig. 16(e). This is called the heliostat field or central receiver collector. By using slightly concave mirror segments on the heliostats, large amounts of thermal energy can be directed into the cavity of a steam generator to produce steam at high temperature and pressure. The concentrated heat energy absorbed by the receiver is transferred to a circulating fluid that can be stored and later used to produce power. Table 4 compares different solar thermal collectors for same capacity of desalination in the context of Sultanate of Oman. Both non-concentrating and concentrating collectors are compared with each for different important factors from scale 1 to 5. 1 indicates the lowest weightage while 5 indicates the highest for the given factor.

Non-concentrating collectors such as FPC, ETC and CPC requires comparatively larger surface area as compared to concentrating collectors. As per a thumb rule one m^2 of parabolic trough is equivalent to 2 m^2 of ETC [68]. Due to this the cleaning and operational cost for non concentrating collectors is more when compared to PTC and other concentrating collectors. Also, the land requirement for same desalination capacity with these collectors will be higher when compared to concentrating collectors. Thus these collectors are mostly suitable for lower and domestic scale desalination requirements.

PDR and HFC reflectors are having higher concentration ratios with higher temperature range. HFC's especially requires larger area and highly skilled operational labor and thus not cost effective for lower to medium temperature applications. Due to this they are used for very high temperature applications including power generation and not suitable for medium to lower capacity desalination requirements. PDR comparatively requires less area but demands for highly skilled labor and compared with other concentrators involves complex operating mechanism. At the same time PTC, PDR and HFC's requires more installation and commissioning time due to their complex technical requirements.

Additionally, PDR, PTC and HFC's require continuous precise 2-axis tracking for their operation. Almost all the commercial installations with these technologies use the computer controlled systems for this purpose, the cost of which is justified with the large scale applications involved. Due to this these technologies are not cost effective for the lower to medium capacity applications. In addition to this, for PDR and PTC, the focus for them lies in the path of the incident beam radiations and receiver is an integral part of the reflector and has to be continuously tracked along-with the reflector to maintain the focal point. This limitation is solved by the Scheffler Dish Reflector (SDR) fixed focus collector which not only provides simple and precise automatic tracking but also a fixed focus away from the path of incident beam radiations. Two SDR installations recently carried out at our institute shown comparatively lower installation and commissioning time. A 100 liters/day desalination set up applying SDR was available for testing within seven working days from the landing date. This could be credited to the lower number of components involved in the SDR based systems. Moreover lower number of components reduces the transportation and logistics cost involved along with the installation time for SDR as compared to other concentrators.

Along with these benefits, compared to other concentrators SDR has lower maintenance and skilled labor requirements [31] with moderate to lower equipment costs and cleaning requirements. Also this type of concentrators can be completely fabricated in an ordinary workshop and thus requires comparatively lower technical requirements. These advantages prevail over the lower efficiency issue of SDR [31] due to larger image at the absorber (lower concentration ratio) and make them best suited option for coupling with decentralized medium to small capacity thermal desalination applications in Sultanate.

6. Solar Thermal Desalination

Thermal desalination is a phase change process and this process is used from ancient time for the conversion of sea water to potable water for drinking purpose. The simple thermal desalination system, also known as single effect desalination process, is shown in Fig. 17. It uses heat energy from combustion of fossil fuels to evaporate the sea water stored in a vessel. The vapors obtained from the evaporation are condensed in a condenser to obtain the condensate as the distilled water for drinking purpose. About 30-60% of the sea water is converted to potable distillate based on the salinity of the sea water in this process. The rest of the sea water, known as brine, is concetrated with salt and not useful for further conversion. It is then disposed of to the surroundings. Thermal losses occur at each stage in the process from combustion of fuel to the distillate making the process highly inefficient.

Thermal desalination processes are practically employed with sea water of any salinity and has very less water treatment requirements. Due to this, these technologies are very popular in the region with high salinity sea water and share almost 34% of the World's [32][33] and almost 64% of MENA region [34] total installed desalination capacity.
Over the years different thermal desalination technologies have been introduced to meet the increasing demand of the desalinated water for drinking as well as industrial applications. These processes include:

A) Indirect Desalination technologies
  i) Multi Effect Desalination (MED)
  ii) Multi Stage Flash (MSF)
  iii) Vapor Compression (VC)
    a. Thermal Vapor Compression (TVC)
    b. Mechanical Vapor Compression (MVC)
  iv) Freezing (heat extraction)

B) Direct Desalination technologies
  i) Humidification / dehumidification (HD)
  ii) Solar Stills

MED, MSF and Vapor compression processes are the traditional indirect desalination technologies used for thermal desalination of low, medium and large capacity output, while solar stills are used as direct type desalination process suitable for low capacity domestic applications. MED and MSF processes that involves heat addition are suitably employed in commercial standalone and combined power and desalination cogeneration plant. A combined power and desalination cogeneration plant produces the electrical power and the desalinated water. This plant utilizes the waste heat along with the direct steam from the power plant for running the thermal desalination process. Vapor compression is combined with MED and MSF to improve process efficiency. Comparatively, freezing (involves heat extraction) and humidification/dehumidification desalination processes are still in the development stage and very few pilot desalination plants have been developed and no commercial installations are reported based on these technologies.

6.1 Multi Effect Desalination (MED)

Fig. 18 shows a Forward Feed type MED (FFMED) process that involves vaporization of sea water in the first effect by using thermal energy from the motive steam, generated using from the combustion of fossil fuels or solar thermal energy or waste heat from the cogeneration plant. The brine water from the first stage is then pumped to the second stage. The vapors generated in the first stage are then used to generate the vapors in the second stage. The vapors in the second stage are then used to generate vapors pumped from brine water pumped from second stage in the third stage and so on. At each stage, the latent heat of condensation of the vapors from the previous stage is utilized to evaporate the sea water in the next stage. Due to this the pressure and thus the temperature in the subsequent stages reduces from first stage to last stage. The condensate obtained from all the stages is collected as desalinated water while the brine collected from all the stages is passed through the feed water pre-heater and finally disposed off to the surroundings. In a back ward flow type MED arrangement, sea water preheated from the condenser enters in the n^{th} stage of the process which is maintained at lowest pressure amongst all. The sea water receives the latent heat of condensation from the vapors of the n-1 stage and flashes to the steam vapors, which are condensed into the condenser to produce the distillate output from the last stage. The sea water brine from nth stage then enters the n-1 stage where, it vaporizes by absorbing the latent heat of condensation of the vapors from the n-2 stage. The remaining brine from the n-2 stage is then pumped back to the n-3 stage and so on. The brine water entering in the first stage receives the latent of evaporation from the motive steam. The vapors generated are then passed to heat the sea water brine received from the third stage and so on. The pressure and temperature maintained in each stage increases from nth stage to the 1^{st} stage. The brine solution from the first stage is with highest salinity and discarded to the surroundings. The distillate collected from 2^{nd} stage onwards is collected together as the total output from the system. In a parallel/cross flow arrangement, sea water from the condenser enters at a time in all the stages and vaporizes by absorbing the heat of condensation from the vapors received from the previous stages. Moreover the brine solution from previous stage is pumped to the next stage maintained at lower temperatures and pressures. Some quantity of the high temperature brine entering into next stage, which is maintained at lower pressures as compared to earlier stage, flashes into steam vapors. This increases the evaporation rate as compared to the other two types.

The performance ratio of the forward feed, backward flow and parallel/cross flow MED process increases with the number of effects. Also for forward feed the performance ratio is almost independent of the top brine temperature in the process [35]. Thus compared to Parallel/cross flow and Backward flow FFMED could be operated at higher top brine temperature.

Studies [35] [36] [37] shown that:
i) Specific heat transfer area and the Gain to Output Ratio (GOR) increases and specific heat consumption decreases with increasing number of effects.
ii) Specific heat transfer area and GOR gets higher and specific heat consumption gets lower with the increasing temperature difference per effect for all the configurations.
iii) Higher operating temperatures and high temperature sea water are favored for all the configurations as it reduces the specific heat transfer areas drastically and reduces the amount of steam required respectively. This increases the GOR for all the configurations.
iv) Parallel/cross flow type shows lower specific heat consumption, higher GOR and better performance ratio when compared with forward and backward feed arrangement.
v) However, Parallel/cross flow feed has higher specific heat transfer area as compared to forward flow due to heating of the feed water in each stage from intake feed water temperature to saturation temperature.

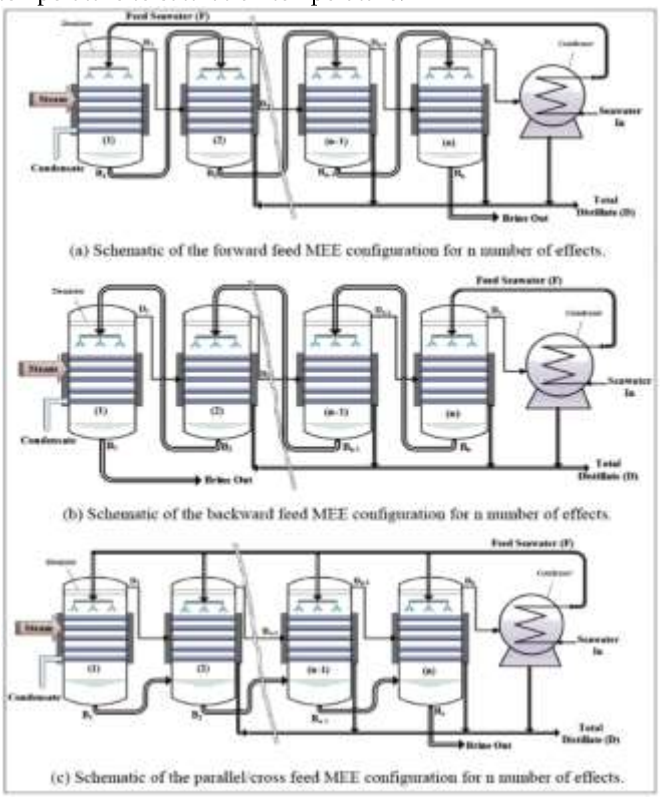

(a) Schematic of the forward feed MEE configuration for n number of effects.
(b) Schematic of the backward feed MEE configuration for n number of effects.
(c) Schematic of the parallel/cross feed MEE configuration for n number of effects.

Fig. 18: Multi Effect Distillation (MED) Process [36]

The MED system operates at an average top temperature of 70^0C. Due to this MED is considered as one of the most suitable process to combine with solar thermal systems. Moreover, due to lower average temperature in the process the potential risk of scale formation in the plant also reduces but this increases the need for higher heat transfer areas. However when combined with vapor compression, the number of effects and the surface area reduces considerably [38]. This process almost contributes to 7.2 % of World's and 11% of MENA region total installed desalination capacity.

6.2 Multi Stage Flash (MSF)

This process as shown in Fig. 19, involves flashing/vaporization of the sea water by suddenly exposing it to low pressure into an evacuated or low pressure chamber and passing it stage by stage to successively decreasing pressure chambers that are maintained at lower temperatures. The steam/vapors generated due to flashing are condensed over the condenser tubes to form the distillate. System requires steam at 100 - 110^{0}C and performance of the system is limited due to lower temperature limit to avoid detrimental scaling formation and accelerated corrosion of the metal parts during the process.

Increased scale control through chemical use, improved process automation and control, improvement in material of construction and improved attention to daily operation has significantly increased the reliability of the process and plant durability over the last few decades. Lower water quality requirements, suitability for higher salinity sea water, producing high quality water with TDS < 5 -10 mg/L, increased reliability due to above stated reasons and reduction in the unit cost and material cost due to significant research in the process has made MSF as the most accepted and preferred commercial thermal desalination technology in the world of desalination. Moreover MSF plants are used with power plants in cogeneration which not only increases the plant efficiency but also reduces the impact of MSF plant on the environment (Making water desalination option or distraction for a thirsty world, Phil Dickie, 2007)[39]. MSF commercial installation capacity ranges from 5000 m^3/day to the maximum capacity 91000 m^3/day [69]. This process almost contributes to 26.8 % of World's and 53% of MENA region total installed desalination capacity.

MSF although considered as the most suitable thermal desalination process commercially due to its simplicity in design and operation, requires precise pressure levels at different stages. Due to this some transient time is required to establish the normal running of the system initially. This feature makes MSF unsuitable / less suitable for solar application. This difficulty could be overcome with the use of storage tank for thermal buffering at extra cost [41].

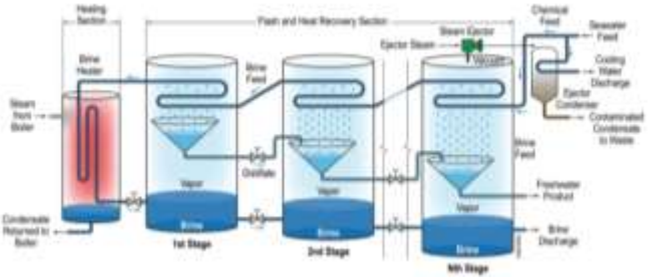


Fig. 19 Multi Stage Flash (MSF) Process [40]

6.3 Vapour compression (TVC and MVC)

Performance of MED system can be improved by using the MVC and TVC methods. These methods involve raising steam pressure using either a compressor in MVC or a steam jet condenser in case of TVC. Mechanical compressors used in MVC system is major source of energy input and incur higher capital cost requirements. Availability of high pressure steam in the range of 2 to 10 bar based on the capacity of the system is the major requirement of the TVC system. Significant improvement in the performance of MED system is observed when combined with MVC or TVC.

Due to the mechanical power input requirement for MVC, TVC is considered to be more effective as compared with MVC. But as both of these technologies have higher energy and capital cost requirements are more justified with larger plant capacities.

6.4 Freezing (Heat extraction)

Freezing and humidification/dehumidification technologies also involve the phase change processes to obtain the desired effect of desalination [41]. Freezing desalination process involves cooling of the sea water below its freezing temperature based on its salinity to obtain the ice crystal floating on the sea water surface, leaving behind the concentrated brine. These crystals are then removed mechanically and then re-melted to obtain the fresh water. Higher capital cost – more than 2 to 3 times the traditional, higher operating cost, complexity of the process, contamination of refrigerant with water, less technological developments in the field are few of the factors which makes this technology not commercially viable [42]. No commercial installation with this technology is available except a pilot plant built in Saudi Arabia in 1987. The combined solar freezing desalination plant based on absorption refrigeration technology producing 180 m3/day was built in 1987 that operated for 2 years [43].

6.5 Humidification / Dehumidification (HD)

Humidification / dehumidification process uses the evaporative cooling principle that involves use of air for humidification and dehumidification. The humidification capacity of air increases with temperature of the air. Air between 60 – 80oC is used during the process. The humidified air coming over the sea water is further cooled during the dehumidification to produce the fresh water. Technological issues, complexity involved in the process, higher production cost, lack of technological development and testing data availability in the field are few of the barriers in the commercial implementation of the technology [46]. Except a few pilot plants installations for small scale and a recently filed patent [44] in the field the technology is still in the development stage for commercial use.

6.6 Solar stills – direct desalination

Solar stills are the most popularly used simple, easy and cheapest direct desalination technology for small scale application yielding from 2 to 11 liters/m2/day with maximum efficiency of 60%. Several factors including material used, ambient conditions, solar irradiation, tilt angle, depth of water in the still, salinity of water, type of insulation, etc. Affects the performance of the solar still. Fig. 20 shows a single and double slope type solar stills most widely used worldwide.

Several modifications in terms of absorber material, system design, retrofitting – such as additional reflectors, use of additional condenser, etc, integration with FPC's or EPC's, increase the transmissivity of glazing, increase absorptivity of absorber plate and water with special type coating for absorber plate and mixing black color in water, changing inclination of absorber surface, increase the basin water temperature, use of weak, increasing number of basins, cooling the cover surface, coupling with : flat plate collectors, evacuated tube collectors, heat pipe Collectors, etc. are used for improving the overall efficiency and yield from the still. Recently a study shown that with use of nano fluids – mixing nano sized particles of aluminum oxide with water, the overall productivity could be increased by 116% due to enhanced evaporative rates when coupled with external condenser [47]. Although solar still offers very simple and cheapest solution for desalination, due to its lower yield, not suitable for medium or large capacity applications. They are mostly suitable for domestic and small capacity less than 50 m^3/day maximum applications only [48].

Table 5: Comparison of different thermal desalination technologies for same capacity – Oman (on scale of 1 to 5: 1 – Low, 5 – High)[49][42][50][51][52][53][54][28][55][56][48][30][57]

Desalination Technology	Complexity of Process	Ease of operation	Capital cost	Development status	Maintenance requirement	Cost per litre	Energy consumption	Salinity of produced water, ppm	Plant Size	Skilled labour requirement	Conversion ratio	Remark
MED	2-3	2-3	2	3-4	2-3	1-2	1-2	1	1-2	2-3	4-5	
MSF	3	3-4	2-3	4-5	3-4	2-3	3	1	1-2	3-4	3-4	Less suitable to couple with Solar energy
Freezing	5	5	3-4	1	3-4	2	3-4	2-3	4	4-5	2-3	
HD	3-4	4-5	4-5	1-2	3-4	4-5	3-4	5	4	4-5	1-2	
Solar Still	1	1	5	4-5	1-2	5	5	2-3	5	1	2-3	

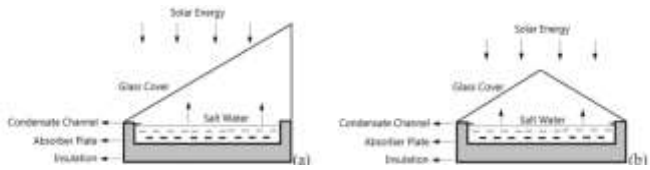


Fig. 20: (a) Single slope single basin type and (b) Double slope single basin type solar still [46]

A comparison of different solar thermal desalination technologies for different important factors with scale 1 to 5 in the context of Sultanate of Oman has been presented in Table 5: 1 indicates the lowest weight age while 5 indicates the highest for the given factor. Freezing and HD techniques are the most complex over the other technologies while direct desalination solar still is the most simpler for complexity of process and operation. As discussed earlier, freezing and HD are still in the pilot stage while solar still and MSF along with MED are most developed and practiced worldwide for commercial and domestic desalination for different capacities. For same capacity (medium to large), being non concentrating type and lower efficiency, cost per liter, energy consumption and plant size will be highest for solar still when compared with rest while MED and MSF stands comparatively moderate to low. Maintenance and skilled labor requirement for solar still will be lowest when compared with rest. Requirement of skilled labor and maintenance for MED is comparatively lower next to solar still in the list. Additionally the salinity of the produced water with MED and MSF is the lowest amongst the other technologies while it is highest for HD [49]. Although solar still seems to be simpler and easier in operation, maintenance, etc., only suitable for lower capacity domestic applications (<50 m^3/day) with maximum output of 11 liter/day/m^2. Moreover, MSF as mentioned earlier is less suitable to couple with solar thermal desalination. In addition, freezing and HD techniques are more complex and still in the pilot stage of development. Thus MSF, freezing and HD technologies are not suitable for desalination in Sultanate of Oman when coupled directly with solar thermal energy.

7. Challenges and Barriers in Implementation of Solar Thermal Desalination Systems

As discussed in earlier section, most of the dessert region in the country receives average DNI 2000 kWh/m^2 yearly in most locations, with higher altitudes receiving over 2500 kWh/m^2. This makes Oman one of the best destinations in the world for implementation of solar thermal applications including desalination.

Even though solar thermal has tremendous potential for the country, still this potential has not been tapped appropriately to the most possible extent. Not many solar thermal installations are implemented in the country. At present desalination in the country in the country is entirely dependent on the use of natural gas and solar energy has no role in the desalination industry. Following are few of the reasons for almost negligible utilization of solar energy for the desalination:

7.1 Economics involved

More than 80-85% of the installed desalination plants in the country are associated with power plants using CCGT technologies. These installed and the proposed new plants are based on RO technologies that utilize electricity generated from these plants for their operation. Remaining plants that are standalone and decentralized type also uses conventional fuels for their operation as almost all of them (except few installations based on MSF technology) are based on RO technologies. Today Oman's 85 % of the revenue is from on Oil and gas export [58]. Being oil and gas producing country, the availability of the natural gas is at subsidized lower cost for the operation of these plants. This yields lower cost per litre of the desalted water. Moreover the land requirement for the CCGT desalination plant is less when compared with decentralized type. On the contrary, solar thermal desalination plant installation with CSP technology such as PTC requires larger land and yields higher cost per liter of desalted water due to additional cost on equipment for collection, storage and transportation of heat accompanied with additional cost for land, installation, commissioning and recurring cost for operation and maintenance. The CSP equipment cost has significantly reduced continually due to research and development in the field in recent years. As per a study carried out cost per liter is almost getting leveled with conventional fuels with RO for sea water desalination while it is still higher for brackish water [56]. It is expected that the cost per liter with solar energy utilization using CSP will further reduce and will surpass conventional fuels in next 10 years [45]. This could be credited to the increasing fossil fuel cost and research and development in the CSP technology.

7.2 Government policy and support

Political support is of prime importance in the development and utilization of any renewable technology in the country. As long as the renewable energy source is not financially and economically competitive in the market, political support is needed for its promotion and encouragement [59]. IRENA report published in 2014 [4] has recommended need for development of renewable energy policy and regulatory framework for renewable energy. This report further recommended target setting for renewable energy implementation, comprehensive programmes in renewable energy, promoting public private partnership, encourage private sector for investing into renewable energy, etc as a part of strategic requirements for encouraging use of renewable in the country. Successful implementation of government policies for promoting the solar energy needs to be achieved by providing financial support in equipment purchase, subsidized taxes for solar thermal equipments, support research and development promotion in solar thermal desalination, supporting training and education programmes in the field, encouraging and supporting private sector to set up SME in the field, etc. Moreover government could also set up decentralized solar thermal desalination units with lower yields (<10000 liters/day) in remotely located villages satisfying the local needs. Additionally combined CSP - gas turbine power plant should be promoted for the commercial implementation [60].

7.3 Technical expertise and experienced workforce in the field

Experienced local and expatriate workforce and technical expertise available in the country is in the field of oil & gas, construction and other specific fields as per the current development in the country. Even the industries and Small and Medium scale Enterprises (SME) are set up as per the local needs of the oil and gas companies. None of the industry or SME in the country is manufacturing in the field of renewable energy. Installation and operation of solar thermal desalination plants requires trained and expert manpower in the field. The local fresh and experienced workforce available has no experience in the field of renewable energy. The availability of such experienced and trained manpower is scarce in the field due to negligible stress on the local training and educational opportunities in the field of solar thermal. As stressed by IRENA report for Oman [4], there is an urgent need for developing educational and training programmes in the field for capacity building of the nation.

7.4 Insufficiently developed technological transfer and research

Due to very low present and future predicted yearly precipitation and falling ground water levels with increasing salinity of soil, desalination is of prime importance in the country to satisfy the increasing fresh water demand due to population growth, urbanization and industrial development. Being oil and gas producing country, the technology transfer and the subsequent development is prone towards the oil and gas sector. Almost more than 90% of the installed desalination plants in the country are based on RO technology and none of the plant is based on MED technology. Only 2-3 installed plants are working on MSF technology. The research and development efforts in the field of desalination in the country are quite less and more focused towards RO technology. This is due to mainly two reasons: firstly the technical advancements of RO technology and secondly the lower cost per liter for RO desalination when coupled with CCGT and OCGT plants. Moreover experience with MSF plants yielded higher maintenance cost when compared with RO technologies. Due to this negligible stress is given for thermal desalination and is based on solar thermal desalination. This gap needs to be analyzed and filled with appropriate collaborations and supported research in the field. Moreover it should be noted that PV-RO systems has lesser efficiency and very expensive when compared with direct solar thermal desalination technology [25].

8. Conclusion

Sultanate of Oman is a tropical country receiving very low precipitation per year. The fresh water demand is rising at 5-8 % annually due to urbanization, life style improvement, profound economical and industrial development in last decade. The gap between demand and supply of fresh water is satisfied using desalination plants since 1976. The desalination capacity in the country has increased almost 60 times that in 1976. Conventional ground water sources continue to satisfy today also almost 80% of the total fresh water demand. This has caused rapid fall in the ground water level with increased soil salinity affecting the yielding capacity of the land.

All the installed commercial desalination plants uses conventional fuels such as natural gas and located mostly in the vicinity of the urban population. Almost 80- 85% of these plants are based on RO technology and coupled with power plants for their electricity requirements. Very few standalone desalination plants are available for rural population. The fuel consumption from these combined desalination plants in increasing at an average rate of 2-3% annually affecting the net export of the country.

Solar and wind energies are considered as the most suitable renewable options for Oman to meet the goal of satisfying minimum 10% requirement of electrical and water by 2020 as per the policy of “Vision 2020”. Almost all the regions of country receives average daily sum of global horizontal irradiation between 6 – 6.75 kWh/m^2 with higher sky clearness index annually. Due to this Oman is considered as one of the best destination for solar thermal applications. But still the real potential of solar energy in the country has not been tapped to the most possible extent. Almost negligible solar thermal installations are implemented in the country. The oil economy factor involved, government policy and support, scarcity of technical expertise and experienced workforce in the field and insufficiently developed technological transfer and research in the field are few of the reasons for negligible utilization of the solar thermal energy in the country.

Solar photovoltaic (PV) system performance gets affected with increasing ambient temperatures, humidity and dust. PV integrated desalination systems offers very low efficiencies when compared with thermal concentrators.

A comparison between different thermal desalination technologies based on several factors namely: ease of operation, complexity of processes, capital cost involved, development status, maintenance requirement, cost per liter, energy consumption, salinity of water produced, plant size, skilled labour requirement and conversion ratio for same capacity of desalination in the context of Oman has been presented in the paper. Multi effect desalination (MED) offers several advantages over the other indirect thermal desalination technologies when integrated with solar thermal concentrators.

Different solar thermal concentrators have also been compared for their temperature range, ease of installation, equipment cost, cleaning and operational requirements, maintenance requirement, land requirement, skilled labour requirement and suitability for same capacity in the context of Oman. Fixed focus type Scheffler dish reflectors (SDR) offers several advantages over other concentrators for lower to medium capacity standalone desalination plants.

Amongst the different desalination technologies, solar stills are best suited for domestic type application below 200 liters/day while MED systems are better option for integration with solar energy over other technologies for higher desalination output requirements. Desalination systems working on MED combined with SDR is more appropriate option for lower to medium capacity decentralized standalone applications. Moreover integrating MED and Parabolic Trough Collectors (PTC) with conventional fuels or combining PTC-MED systems with CCGT or OCGT plants while utilizing the waste heat from these plants would be a feasible solution for higher capacity desalination output.

9. Acknowledgement

The research leading to these results has received Project Funding from The Research Council of the Sultanate of Oman under Research Agreement No. ORG/CCE/EI/13/009. Authors would acknowledge the support and encouragement received from The Research Council as well as Caledonian College of Engineering, Muscat Sultanate of Oman.

References

[1] Ministry of Regional Municipalities and Water Resources (MRMWR), “Water resources in Oman”, 2008.
[2] S. Al Shibli, “Sultanate of Oman’s Strategy for Securing Water Resources”, 2014.
[3] Imen Jeridi Bachellerie, Ed., “Renewable Energy in the GCC Countries”, 2012th ed. Gulf Research Center.
[4] International Renewable Energy Agency, “Renewables Readiness Assessment”, 2014.
[5] Oman Power and Water Procurement Company (OPWP), “OPWP’s 7-YEAR STATEMENT 2017-2023”, 2017.
[6] International Water Management Institute, “Helping the world adapt to water scarcity”, 2008.

[7] Taha Al-Farra, "Water Security in the Gulf Region", pp. 1–18, 2015.
[8] U. Nations, "Water for a Sustainable World ", 2015.
[9] OPWP, "OPWP's 7-YEAR STATEMENT 2007 – 2013", 2006.
[10] A. A. A. Abulllah Mohamed Al-Mutawa, Waleed Mohamed Al Murbati, Nasser Ahmed Al Ruwaili, Ahmed Sulaiman Al Oraifi, Abdulrahman Al Oraif, "Desalination in the GCC history present and future", The Cooperation Council for the Arab States of the Gulf (GCC), 2013.
[11] OPWP, "OPWP's 7-YEAR STATEMENT 2015-2021" , 2015.
[12] AL Mohammed, "Chapter No. 6: The Vision for Oman's Economy: Oman 2020.," no. 6, pp. 125–164, 2012.
[13] A. H. Al-Badi, A. Malik, and A. Gastli, "Assessment of renewable energy resources potential in Oman and identification of barrier to their significant utilization", Renew. Sustain. Energy Rev., vol. 13, no. 9, pp. 2734–2739, 2009.
[14] A. Gastli and Y. Charabi, "Solar electricity prospects in Oman using GIS-based solar radiation maps", Renew. Sustain. Energy Rev., vol. 14, no. 2, pp. 790–797, 2010.
[15] Y. Al Charabi and S. Al-Yahyai, "Projection of Future Changes in Rainfall and Temperature Patterns in Oman", J. Earth Sci. Clim. Change, vol. 4, no. 5, pp. 1–8, 2013.
[16] K. A. Moharram, M. S. Abd-Elhady, H. A. Kandil, and H. El-Sherif, "Enhancing the performance of photovoltaic panels by water cooling", Ain Shams Eng. J., vol. 4, no. 4, pp. 869–877, 2013.
[17] A. Gastli and J. S. M. Armendariz, "Challenges facing grid integration of renewable energy in the GCC region", EU-GCR Renew. Energy Policy Expert. Work., no. December, 2013.
[18] A. Gastli, "Integration of temperature and dust effects in siting large PV power plant in hot arid area", Renew. Energy, vol. 57, no. December 2016, pp. 635–644, 2013.
[19] A. Gastli, "Spatio-temporal assessment of dust risk maps for solar energy systems using proxy data", Renew. Energy, vol. 44, no. August 2012, pp. 23–31, 2012.
[20] S. A. Kalogirou, "Solar thermal collectors and applications", Progress in Energy and Combustion Science vol. 30, no. 3., pp. 231-295, 2004.
[21] G. Morin, J. Dersch, M. Eck, A. Häberle, and W. Platzer, "Comparison of Linear Fresnel and Parabolic Trough Collector Systems - Influence of Linear Fresnel Collector Design Variations on Break Even Cost", Proceedings of 15th International SolarPACES Symposium, 2009.
[22] N. El Gharbi, H. Derbal, S. Bouaichaoui, and N. Said, "A comparative study between parabolic trough collector and linear Fresnel reflector technologies", Energy Procedia, vol. 6, pp. 565–572, 2011.
[23] WORLD ENERGY COUNCIL, "World Energy Resources Solar 2016", 2016.
[24] [24] GlassPoint Solar, "One Gıgawatt Solar Thermal Project To Generate Steam For Oıl Productıon", 2017.
[25] M. A. Darwish, H. K. Abdulrahim, A. S. Hassan, A. A. Mabrouk, H. K. Abdulrahim, A. S. Hassan, and A. A. M. Pv, "PV and CSP solar technologies & desalination : economic analysis", Desalin. Water Treat., vol. 57, no. 37, pp. 1–23, 2015.
[26] S. Kalogirou, "Use of parabolic trough solar energy collectors for sea-water desalination", Appl. Energy, vol. 60, pp. 65–88, 1998.
[27] T. Hirsch, J. F. Feldhoff, and M. Wittmann, "Energetic Comparison of Linear Fresnel and Parabolic Trough Collector Systems," vol. 136, no. November, pp. 1–11, 2014.
[28] Houda Ben Jannet Allal, "Combined Solar Power and Desalination Plants : Techno-Economic Potential in Mediterranean Partner Countries", MED - CSD, 2009.
[29] J. D. Nixon, P. K. Dey, and P. A. Davies, "Which is the best solar thermal collection technology for electricity generation in north-west India? Evaluation of options using the analytical hierarchy process", Energy, vol. 35, no. 12, pp. 5230–5240, 2010.
[30] N. Ghaffour, J. Bundschuh, H. Mahmoudi, and M. F. A. Goosen, "Renewable energy-driven desalination technologies: A comprehensive review on challenges and potential applications of integrated systems", Desalination, vol. 356, pp. 94–114, 2015.
[31] J. Ruelas, N. Velázquez, and R. Beltrán, "Opto – geometric performance of fixed-focus solar concentrators", Sol. Energy, vol. 141, pp. 303–310, 2017.
[32] A. A. Mabrouk, "Techno-economic analysis of tube bundle orientation for high capacity brine recycle MSF desalination plants", Desalination, vol. 320, pp. 24–32, 2013.
[33] C. Li, Y. Goswami, and E. Stefanakos, "Solar assisted sea water desalination : A review", Renew. Sustain. Energy Rev., vol. 19, pp. 136–163, 2013.
[34] H. Sewilam and P. Nasr, "Desalinated Water for Food Production in the Arab Region", Water-Energy-Food Security Nexus in the Arab Region, W. S. Kamel Mostafa Amer, Zafar Adeel, Benno Böer, Ed. Springer, 2015.
[35] H. M. E. Hisham T. El-Dessouky, "Fundamentals of Salt Water Desalination", Elsvier, 2002.
[36] I. S. Al-mutaz and I. Wazeer, "Comparative performance evaluation of conventional multi-effect evaporation desalination processes", Appl. Therm. Eng., vol. 73, no. 1, pp. 1192–1201, 2014.
[37] İ. Halil and M. S. Söylemez, "Design and computer simulation on multi-effect evaporation seawater desalination system using hybrid renewable energy sources in Turkey", vol. 291, pp. 23–40, 2012.
[38] O. K. Buros, "The ABCs of Desalting," 2000.
[39] P. Dickie, "Desalination : option or distraction for a thirsty world ?", WWF's Global Fresh water Programme, 2007.
[40] V. S. Frenkel, "Seawater Desalination : Trends and Technologies in Desalination", February, M. Schorr, Ed. InTech, 2011, pp. 119–128.

[41] S. A. Kalogirou, "Seawater desalination using renewable energy sources", Prog. Energy Combust. Sci., vol. 31, no. 3, pp. 242–281, 2005.

[42] M. S. Rahman and M. Al-Khusaibi, "Freezing-Melting Desalination Process", Desalination: Water from Water, Scrivener Publishing and John Wiley & Sons, pp. 473-501, 2014.

[43] D. A. Al-Alshaikh, "Seawater Desalination in Saudi Arabia : An Overview." 2012.

[44] S. O. Liburd, "Solar-Driven Humidification Dehumidification Desalination for Potable Use in Haiti", Massachusetts Institute of Technology, 2010.

[45] N. Jamshidi, M. Farhadi, D. D. Ganji, and K. Sedighi, "Experimental analysis of heat transfer enhancement in shell and helical tube heat exchangers", Appl. Therm. Eng., vol. 51, no. 1–2, pp. 644–652, 2013.

[46] E. Deniz, "Solar-Powered Desalination", in Desalination Updates, R. Y. Ning, Ed. InTech, 2015, pp. 89–124.

[47] A. E. Kabeel, Z. M. Omara, and F. A. Essa, "Enhancement of modified solar still integrated with external condenser using nanofluids: An experimental approach", Energy Convers. Manag., vol. 78, pp. 493–498, 2014.

[48] Z. Z. and L. Y. Mohamed A. Eltawil, "Renewable Energy Powered Desalination Systems : Technologies and Economics-State of the Art", in Twelfth International Water Technology Conference, IWTC12, pp. 1099–1136, 2008.

[49] P. G. Youssef, R. K. Al-Dadah, and S. M. Mahmoud, "Comparative analysis of desalination technologies", Energy Procedia, vol. 61, pp. 2604–2607, 2014.

[50] N. Ghaffour, T. M. Missimer, and G. L. Amy, "Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability", Desalination, vol. 309, no. 2013, pp. 197–207, 2013.

[51] A. E. Kabeel, M. H. Hamed, Z. M. Omara, and S. W. Sharshir, "Water Desalination Using a Humidification-Dehumidification Technique - A Detailed Review", Nat. Resour., vol. 4, no. 3, pp. 286–305, 2013.

[52] S. M. Badawy, "Laboratory freezing desalination of seawater", Desalination and Water Treatment, vol. 57, no. 24, pp. 11040–11047, 2016.

[53] R. D. C. Shone, "The freeze desalination of mine waters," J. South African Inst. Min. Metall., vol. 87, no. 4, pp. 107–112, 1987.

[54] K. E. Thomas, "Overview of Village Scale Renewable Energy Powered Desalination", NREL, 1997.

[55] F. Trieb, M. Moser, and T. Fichter, "MENA Regional Water Outlook Part II: Desalination using Renewable Energy ", FICHTNER (Germany), 2011.

[56] F. Diogo, A. Santos, and M. Azevedo, "Renewable Energy Powered Desalination Systems: Technologies and Market Analysis", Masters Thesis, University of Lisbon, 2014.

[57] X. Xu, K. Vignarooban, B. Xu, K. Hsu, and A. M. Kannan, "Prospects and problems of concentrating solar power technologies for power generation in the desert regions", Renew. Sustain. Energy Rev., vol. 53, no. January, pp. 1106–1131, 2016.

[58] N. Al-Mawali, H. M. Hasim, and K. Al-Busaidi, "Modeling the Impact of the Oil Sector on the Economy of Sultanate of Oman", Int. J. Energy Econ. Policy, vol. 6, no. 1, pp. 120–127, 2016.

[59] A. G. A.H. Al-Badi, A. Malik, "Sustainable energy usage in Oman—Opportunities and barriers", Renew. Sustain. Energy Rev., vol. 15, no. 8, pp. 3780–3788, 2011.

[60] M. Moser, F. Trieb, and T. Fichter, "Potential of Concentrating Solar Power Plants for the Combined Production of Water and Electricity in MENA Countries", vol. 1, no. 2, pp. 122–141, 2013.

[61] C. V Sudhir and V. Joy, "Challenges of seawater desalination in oman and study of Lead (Pb), Cadmium (Cd), Nickel (Ni), Chromium (Cr) heavy metals in seawater", Int. J. Adv. Sci. Eng. Technol., vol. 4, no. 2, pp. 47–50, 2016.

[62] Water resources, available from: http://mrmwr.gov.om/new/en/Page.aspx?id=82&li=8&Type=W_Sec&Slide=false, accessed on 07/10/2017.
]

[63] Image reference: Water Availability and Use in the Middle East, http://www.carboun.com/water/water-availability-and-water-use-in-the-arab-world-infographics/, accessed on 07/10/2017.

[64] Image reference: GHI and DNI map of Oman, http://solargis.info/doc/_pics/freemaps/1000px/ghi/SolarGIS-Solar-map-, accessed on 07/10/2017.

[65] Image reference: Solar Technology – Concentrated Solar Power, available from https://lh3.googleusercontent.com/-ACjkO1oR5Og/VSZGr9lu2hI/AAAAAAAACMo/iGdFbw1nKFA/w2416-h896/Main%2BCSP%2Btechnologies.jpg, accessed on 07/10/2017.

[66] Image reference: Flat plate collector, available from: http://www.renewableenergyfocus.com/view/17067/solar-thermal-technology-update/, accessed on 07/10/2017.

[67] Image reference: Scheffler reflector for community kitchen, available from: http://www.solare-bruecke.org/index.php/en/die-scheffler-reflektoren, accessed on 07/10/2017.

[68] Compare with evacuated tube collectors, available from: http://wims.unice.fr/xiao/solar/evacuated.html, accessed on 07/10/2017.

[69] Largest desalination plant produces its first water, Desalination & water reuse, 2014, available from: https://www.desalination.biz/news/0/Largest-desalination-plant-produces-its-first-water/7529/, accessed on 07/10/2017.

[70] Glasspoint Inaugurates First Four Units of Miraah in Oman, 2018, available from: http://www.solarpaces.org/glasspoint-inaugurates-first-four-units-miraah-oman/, accessed on 19/02/2018.

[71] A. Ibrahim, A. A. El-Amin, "Temperature Effect on the Performance of N-type μc -Si Film Grown by

Linear Facing Target Sputtering for Thin Film Silicon Photovoltaic Devices", Internatıonal Journal Of Renewable Energy Research (IJRER), Vol. 2, no. 1, 2012.

[72] Rahnuma Siddiqui and Usha Bajpai, "Deviation in the performance of Solar Module under Climatic parameter as Ambient Temperature and Wind Velocity in Composite Climate", Internatıonal Journal Of Renewable Energy Research (IJRER), Vol. 2, no. 3, 2012.

[73] Sujit Kumar Jha, "Application of Solar Photovoltaic System in Oman –Overview of Technology, Opportunities and Challenges", Internatıonal Journal Of Renewable Energy Research (IJRER), Vol. 3, no. 2, 2013.