Design of CSP plants for desalination in Libya

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Contents

Table of Figures

List of Tables

Acronyms used in this report

CSERS – Centre for Solar Energy Research and Studies (Libya)

DEWI - DEWI (UL International GmbH)

DNI – Direct Normal Irradiance

ED – Electro Dialysis

GDC – General Desalination Company of Libya

GECOL – General Electric Company of Libya

GHI – Global Horizontal Irradiance

GMMR – Great Manmade River

GOR – Gas to Oil Ratio

GW – Ground Water

HD – Humidification Dehumidification

HP – High Power

HTF – Heat Transfer Fluid

LI – Lahmeyer International

LP – Low Power

LWC – Levelised Water Cost

LYD – Libyan Dinar

MED – Multiple Effect Distillation

MENA – Middle East and North Africa

M_f – rate of fresh water production (l/hr)

MSD – Multi Stage Distillation

MSF – Multi Stage Flash Desalination

MSF-BR – Multi Stage Flashing with Brine Recirculation

MSF-OT – Multi Stage Flashing – Once Through process

MSR-BR – Molten Salt Reactor – Brine Recirculation

MSR OR – Molten Salt Reactor – Organic Rankine cycle

NASA – National Aeronautics and Space Administration (USA)

NOR – National Oil Company

NREL – National Renewable Energy Laboratory (USA)

PV – Photo Voltaic

Q_{in} – total solar power incident on solar field (W)

Q_{st} – stored thermal energy (W)

RES – Renewable Energy Sources

RO – Reverse Osmosis

SAM – System Advisor Model

SHDD – Solar Humidification and Dehumidification Desalination

SWRO – Sea Water Reverse Osmosis

TDS – Total Dissolved Solids

TES – Thermal Energy Storage

TESP – Tajoura Experimental Solar Pond

TVC – Thermal Vapour Compression

W_{net} – Net Electricity Produced (W)

WEC – Wind Energy Conversion

ZSW - Zentrum für Sonnenenergie- und Wasserstoff-Forschung Baden-Württemberg (Germany)

1 Introduction

1.1 Background

About 75% of earth's surface is covered by water. Unfortunately, about 97.5% of this water is salt water present in seas and oceans. Only, about 2.5% of it, is fresh water contained in underground and surface waters of which 80% is frozen in glaciers. The remaining percentage of all fresh water is underground in deep and hard to reach aquifers. Only 0.5% of the total fresh water available is contained in the lakes and rivers [1].

Lack of fresh water is one of the main problems that affects many countries around the world. In arid areas, potable or fresh water is very scarce and the establishment of a human habitat in these areas strongly depends on how such water can be made available [2]. Water shortages involve more than 80 countries and 40% of the world population [3]. There are 1.1 billion people without adequate drinking water. Based on forecasts for 2020, it is expected that the world population will reach 7.5 billion of which over 60% will be exposed to water shortages. This is because of the population growth, the higher consumption of water associated with rising standards of living, and increased economic activities. Moreover, common use of unhealthy water in developing countries causes 80-90% of all diseases and 30% of all deaths.

Water scarcity is a growing issue worldwide. It results when the local fresh water demand is similar in size to the local fresh water supply. Figure 1 shows regions of the world in which the amount of water withdrawal approaches the difference between that lost through evaporation and that gained through precipitation, resulting in scarcity [4].

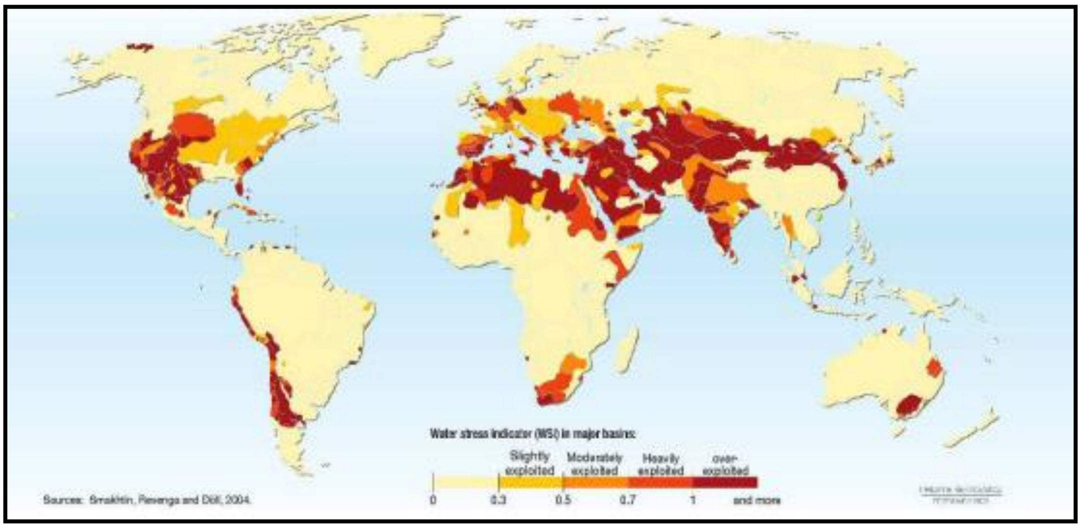

Figure 1: Regions of water scarcity, in which total water withdrawals approach the difference between precipitation and evaporation, are show in orange and red [4].

Desalination technologies play an increasing role in bridging the water gap in many countries. Desalination is defined as a water-treatment process that separates salts from saline water to produce potable water or water that is low in total dissolved solids (TDS). In 2008, seawater desalination accounted for 67% of production, followed by brackish water at 19%, river water at 8%, and wastewater at 6% as shown in Figure 2. [5]

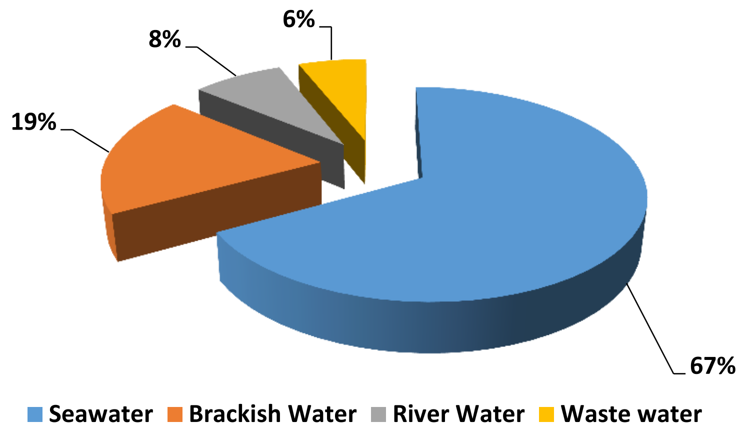

Figure 2: Worldwide feed-water percentage used in desalination [5].

There are over 23,000 desalination plants operational worldwide, with a total operating capacity of 85 million m^3 per day, with 53% of them in the Middle East [6]. In the Middle East and North Africa (MENA) region, the shortage of water is approximately 9.3 billion m^3 will be met mostly through desalination by 2050 [7]. However, desalination is considered the most energy-intensive water production technique. It consumes at least 75.2 TWh of electricity per year, equivalent to around 0.4% of global electricity consumption. Presently fossil fuels are the main source of energy for desalination, with less than 1% of capacity dependent on renewables. Energy is the largest single expense for conventional desalination plants, representing as much as half of the production cost. [7]

Major desalination processes consume a large amount of energy derived from oil and natural gas as heat and electricity, while emitting harmful CO_2 gas. Solar, wind, wave, geothermal and even nuclear sources could provide a viable source of energy to power both seawater and brackish water desalination plants. Seawater desalination is an expensive process, but the inclusion of renewable energy sources and the adaptation of desalination technologies to renewable energy supplies can in some cases be a considerably less expensive and economic way of providing water [8]. Solar desalination has emerged as a promising renewable energy-powered technology for producing fresh water [9].

1.2 Water Situation in Libya

Libya is a sparsely populated North African state with a population of about 6 million and an area of over 1.759 million square kilometres. The climate is mostly semi-arid to arid with very low precipitation rates and limited fresh water sources. It is in one of the driest regions of the world with an annual rainfall ranging from just 10-500 mm, with only 5% of its land receiving more than 100 mm annually10]. Therefore, seawater desalination is the most practical answer to overcome the issue of fresh water shortage. The country's population has tripled since the 1950s. As a result, of this and the improvement of living standards (and therefore the demand for water), the country is confronted with a severe lack of water resources. Water deficits of about 1.15-4.34 km^3 have been estimated for the years 1998 and 2025, respectively [11]. The General Water Authority in Libya in its report in 2006 estimated the water deficit would be 1 to 1.2 km^3 in 2025 [12]. Another study sponsored by the World Bank estimated that the annual demand in the period between 2000-09 by 4.13 km^3, and the expected annual deficit in the period between 2020-2030 would be 1.38 km^3 and will reach to 3.65 km^3 by 2050 [13]. It is estimated that in 2005 the total water consumption was 4.98 km^3 divided into different sectors as shown in Figure 3, and the water resources are as shown in Figure 4 [12].

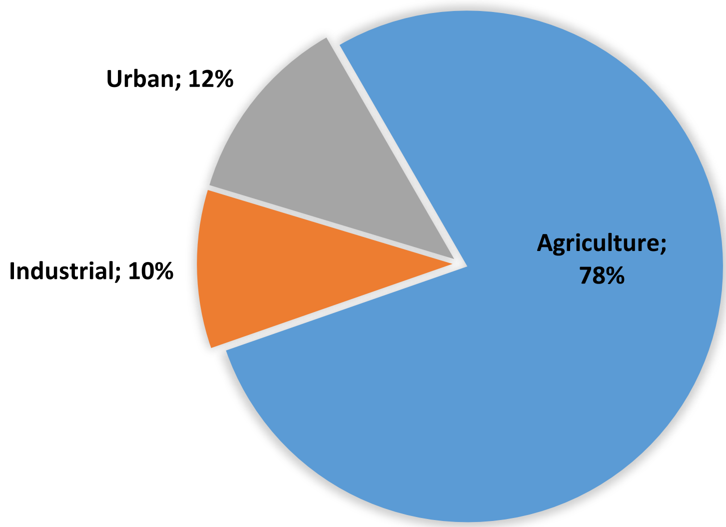

Figure 3: Water usage in Libya, 2006 [12]

Municipal water demand has increased markedly in the last 4 decades in response to high population growth rates and increased per capita requirements. In 2010, per capita water use rates varied from 150 to over 450 litres per day, and if this trend continues, municipal water demand is expected to rise to 0.71 km^3/year in 2015 and to 0.9 km^3/year in 2025. Desalination capacities are expected to rise to 0.5 Mm^3 /day and over 1 Mm^3 /day by 2015 and 2025, respectively. [14]

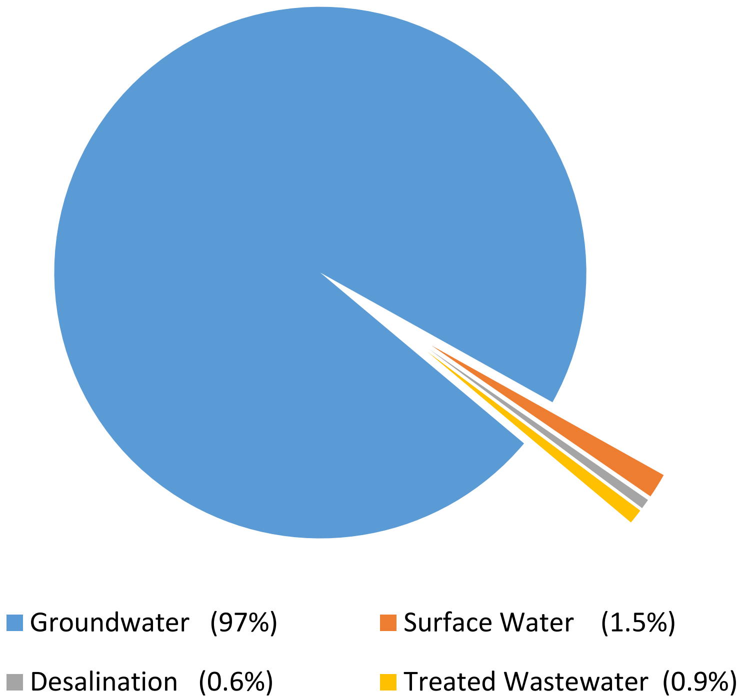

Figure 4: Sources of water supply in Libya in 2006 [12]

The share of the main sources of domestic water supply is as shown in Figure 5. It is very clear in 2012 over 87.6% of the water came from groundwater sources, whereas in 2015 it increased to 92.2%. [15]

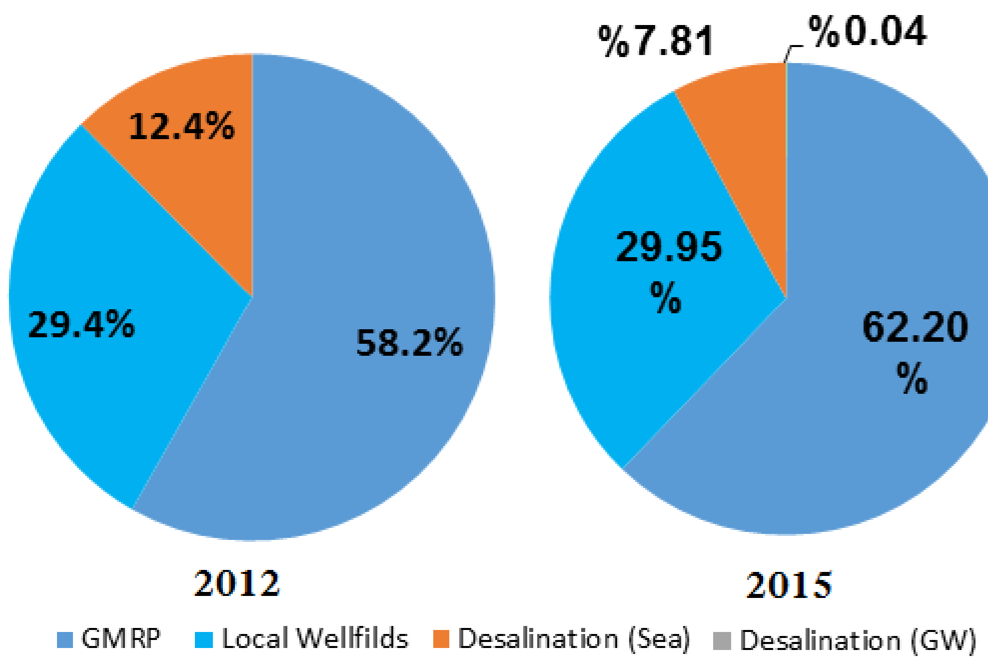

Figure 5: domestic water supply in 2012 and 2015 [15]

The expansion in utilizing groundwater wells causes severe lowering in the water levels in the coastal wells and the possibility of contamination by sea water. There is an urgent need of addressing this problem properly to avoid serious impact on the sustainability of the development of the country.

Transferring water and using desalination plants to supply demand water is energy consuming. In 2010, it is estimated 3.04% of the sold electricity was used by the Great Man-Made River (GMMR) project and 0.88% used by desalination plants as shown in Figure 6. [16]

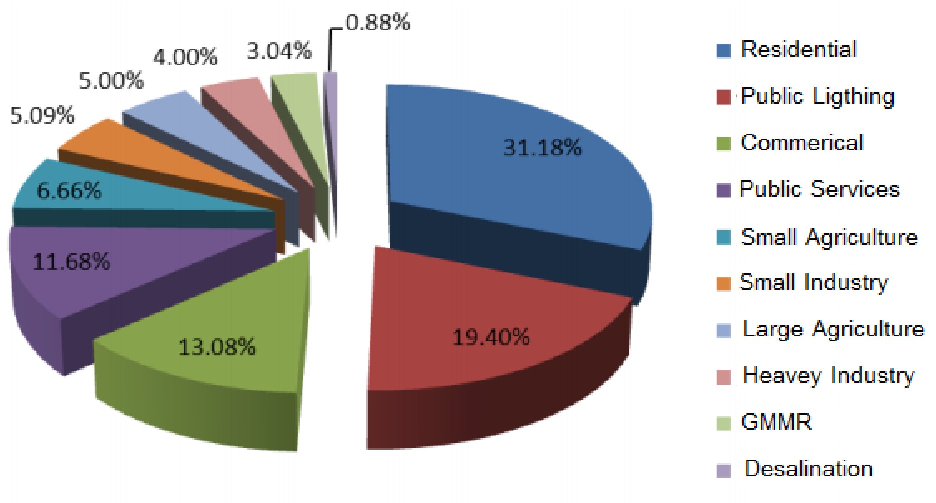

Figure 6: Breakdown of sold electric energy in Libya in 2010 [16]

The amount of energy consumed by desalination plants in 2010 according to the type of fuel is shown in Table 1. [16]

Table 1: water production and energy consumption by desalination plants in 2010 [16].

Plant	Production (m^3)	Energy consumption (MWh)	Fuel Consumption (m^3)		
			Heavy	Light	Gas
West Tripoli	1,545,797	5,580	0	21,079	0
Musruta	3,522,430	38,006	0	0	57,277,442
North Bangazhi	1,903,436	934	0	1,659	2,980,200
Darna	416,837	3,522	917	2,967	0
Azawia	691,289	-	*	*	*
ALkhomus	7,150,519	38,006	0	0	54,362,700
Total	15,230,278	86,048	917	25,705	114,620,342

*Steam used is from power plant steam generation unit

2 Water Resources in Libya

2.1 Surface Water

The dominant features of rainfall are scarcity and variability in intensity from year to year. Therefore, a very small amount of runoff reaches the sea and it is supposed that most of the runoff water is either evaporated or infiltrated into the wadi beds for recharging the underlying aquifers. The total mean annual runoff water is estimated at 200 Mm^3/yr. Even assuming, that 50% of the water can be intercepted and forms a resource, these 100 M m^3/year would represent only 1-2 % of the water resource [17]. Seventeen dams have been built to intercept water runoff. The combined total storage of these dams is 387 M m^3/year and the annual water capacity is 61.8 Mm^3. Another twelve dams are expected to be built within the next few years with a total capacity of 58.63 M m^3/year [12, 18].

2.2 Groundwater Resources

Groundwater is the main water resource in Libya, it constitutes about 97% of the total amount of available fresh water in the country. It is estimated that the annual direct water feed is 0.6 km^3, whereas the total consumption is 4.98 km^3. Over 87% of groundwater is from non-renewable resources. [12]

Libya has five principal regions with substantial water resources:
Jifarah Plain and Jabal Nafusah region, the Middle zone, Al Jabal Al Akhdar r egion, Fezzan region and Kufrah and Assarir region, as shown in Figure 7 [17].

2.2.1 Jifarah Plain and Jabal Nafusah Region

This region which is in the northwest part of Libya represents more than 80% of the irrigated area in the country. The early Cretaceous/Triassic formation contains aquifers with varying degrees of discharge and depth. Water quality ranges from good to saline. The estimated discharge of wells into the shallow aquifers is 2-3 m^3/s. Discharge from the artesian wells is estimated to be around 350 m^3/hr. The current ground water production in this region is approximately 1750 Mm^3/year with salt contents of 400-1000 ppm. [17]

The annual recharge rate is estimated to be around 300 Mm^3/yr. The recharge is mainly from the rainfall on Jabal Nafusah, south of Jifarah plain. Therefore, this aquifer is greatly over exploited and thus non-sustainable. [17]

2.2.2 The Middle Zone

This region constitutes a transition between Jifarah plain in the west, Al-Jabal Al-Akhdar in the east and Fezzan and Al-Haruj Al-Aswad in the south. The region is characterized by Tertiary/Quaternary formations containing shallow aquifers especially along the coast. The depth of these reservoirs ranges between 30 to 100m. There are also deep reservoirs present in the late Cretaceous formation, with depths ranging from 100 to 800 m from the soil surface. There are also Cretaceous aquifers ranging in depth from 70 to 250 m from the soil surface. The current water use is around 400 Mm^3/year. [17]

Figure 7: The locations of water regions in Libya [17]

2.2.3 Al Jabal Al Akhdar Region

This region comprises Benghazi plain as well as the Al-Jabal Al-Akhdar area and extends to the eastern border with Egypt. The ground water reservoir of this area is present in layers of Tertiary limestone formation, sitting on an impermeable layer of late Cretaceous formation. It is characterized by the existence of faults through which water moves northwards, towards the Mediterranean Sea, at rate of approximately 250 Mm^3/year. Another portion of the water in this reservoir moves southwards at a rate of 150 Mm^3/year. The estimated recharge is approximately 340 Mm^3/year. [17]

2.2.4 Fezzan Region

This region is situated in the south-western part of Libya and the groundwater is present in two main aquifers. The first is Nubian sandstone aquifer. The thickness ranges between 50 and 300 m. In some places, it extends to a depth of 800 m.

The second aquifer is present in Devonian and Cambro-Ordovician formations. It is very deep up to 2000 m with a thickness ranging between 300 and 2000 m. The Devonian sandstone is separated from the Cambrian-Ordovician by clay layers, particularly in the western part of the basin. The groundwater recharge in this region is zero due to lack of rain. [17]

2.3 Great Man-Made River (GMMR)

Figure 8. The Great Man-Made River project – installation of pipelines [18]

The GMMR is a large project that developed to tackle the lack of water in Libya, it consists of 4500 km of pipeline network delivering fresh water from Sahara Desert aquifers to the crowded northern coast where the demand locates [19]. In addition, GMMR provides water for many agricultural projects that were established to promote food security as shown in Figure 9. The Libyan government has subsidized GMMR water to be utilized mainly in agricultural developments (70%), then domestic use (27%) and finally for industrial projects (3%). [20,21]

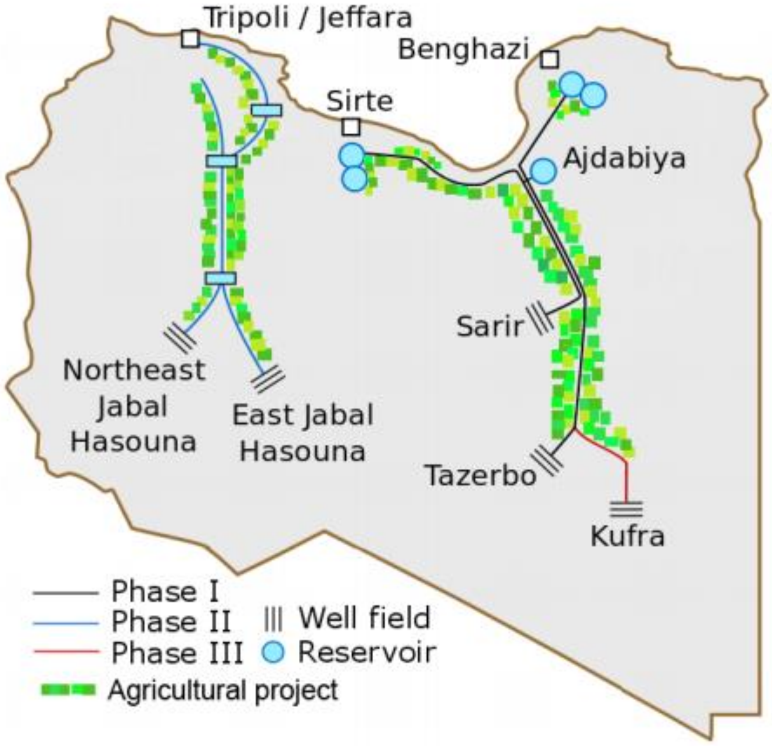

Figure 9: Map of Great Man-Made River [10]

Libya is located on the Mediterranean with a long coast of 1900 m. However, water transfer was selected instead of sea water desalination to provide water for economic reasons at the time. When considering alternatives in the 1980s it was expected that the water transfer process would cost less than 3.18 $/m^3$, while the desalination process would cost 5.5 $/m^3$. However, these numbers changed during the period between 1979 and 1999, when the cost of desalinated water decreased to less than 0.55 $/m^3$. [22]

The largest two phases of the project have already been commissioned and in operation for over 10 years. The present production is approximately 4 Mm^3/day. When the final parts start operating, the total production of fresh water should be 6.6 Mm^3/day.

As indicated in the previous sections, the southern aquifer, which are the main source of the river, has a zero-recharging rate which means the withdrawn water is not being replaced. Therefore, the aquifer could run out.

The challenges against the project could be summarized in two points; first, the decrease in the cost of alternatives processes to supply potable water and second, the low recharging rate of the main aquifers in Fezzan.

2.4 Desalination in Libya

2.4.1 Conventional Desalination Plan

Figure 10: A desalination plant

Different desalination plant technologies are used in Libya, where the total number of units producing quantities of water larger than 100 m^3/day is 425 and the total installed capacity is about 750,000 m^3/day which represents about 3% of the world installed capacity in 2000 as shown in Figure 11. The design capacity of the operable desalination plants in the year 2002 is about 332,930 m^3/day, where thermal processes represent about 63% and the rest are membrane processes [21].

Recently, there are three main authorities with responsibility for operating desalination plants in Libya: General Desalination Company (GDC), General Electric Company of Libya (GECOL), and National Oil Company (NOC). In addition, many other desalination plants are operated by hospital, factories, hotels, and public services. For instance, the Nuclear Research Centre own and operate 1000 m^3/day Reverse Osmosis (RO) desalination plant, an emergency hospital in Tripoli treats brackish water with an RO desalination unit with a capacity 340 m^3/day in addition to an older sea water RO desalination plant with a capacity 650 m^3/day, and Centre for Solar Energy Research and Studies (CSERS) has two units with total capacity of 100

m^3/day. Moreover, domestic scale RO desalination units (0.2–7 m^3/day) are widely spread in the residential and commercial sectors of Libya.

GDC is responsible for the largest thermal desalination plants in the country dedicated to municipal supply. The company owns nearly 29 desalination plants spread all over the coastal line of Libya, and the main operable plants are listed in Table 2. [15,23] Total production in 2011 was 0.5 Mm^3/day for all uses including brackish water sources and small size RO plants for non-urban uses.

Table 2: Desalination plants for municipal supply in 2013 [15, 23]

No	Name	System	Year	No. of Units	Capacity (m^3/day)
1	Bomba	MSF	1988	3	30,000
2	Sousa 1	MED	2000	2	10,000
3	Sousa 2	MED	2011	2	40,000
4	Tobruq	MED	2002	3	40,000
5	Zliten	MSF	1992	3	30,000
6	Zwara	MED	2006	3	40,000
7	Abu Traba	MED	2007	3	40,000
8	Derna	MED	2011	2	40,000
9	Zawia	MED	2011	4	80,000
10	Zwara Ext	MED	2011	2	40,000
	Total			27	390,000

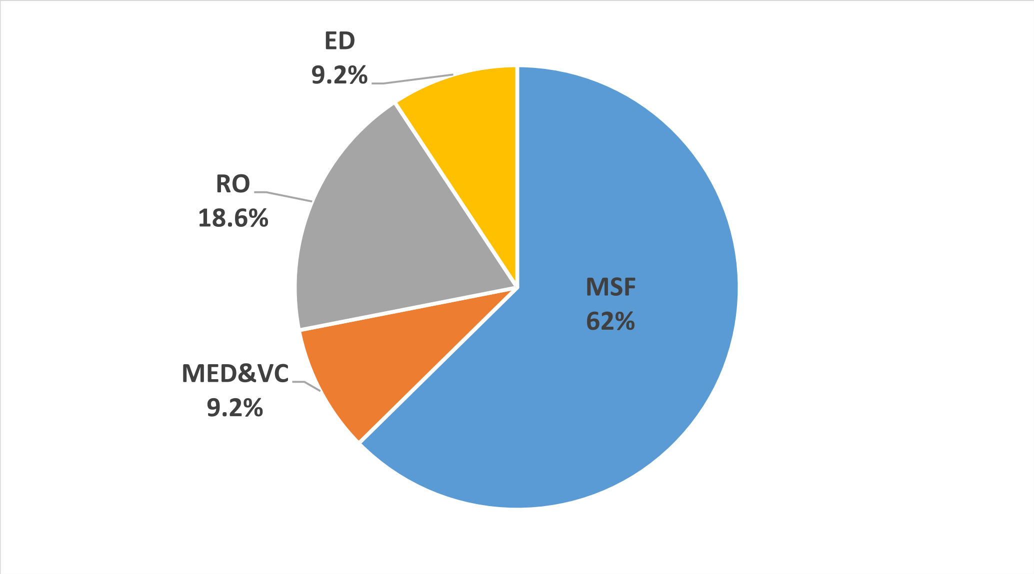

Figure 11: share of desalination plants technology in 2000 [15,23]

The amount of desalinated water over the years is shown in Figure 12. In 2014, it slightly decreased to 61.9 Mm^3 due to maintenance problems [15].

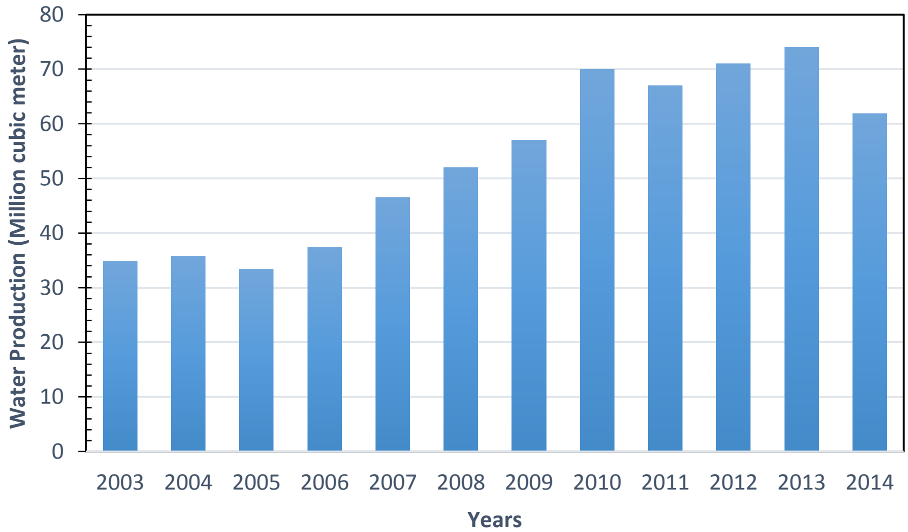

Figure 12: Statistics of desalinated water production [15]

GDC's plan is to install up to 1.35 Mm^3/day over the next years as distributed in Figure 13.

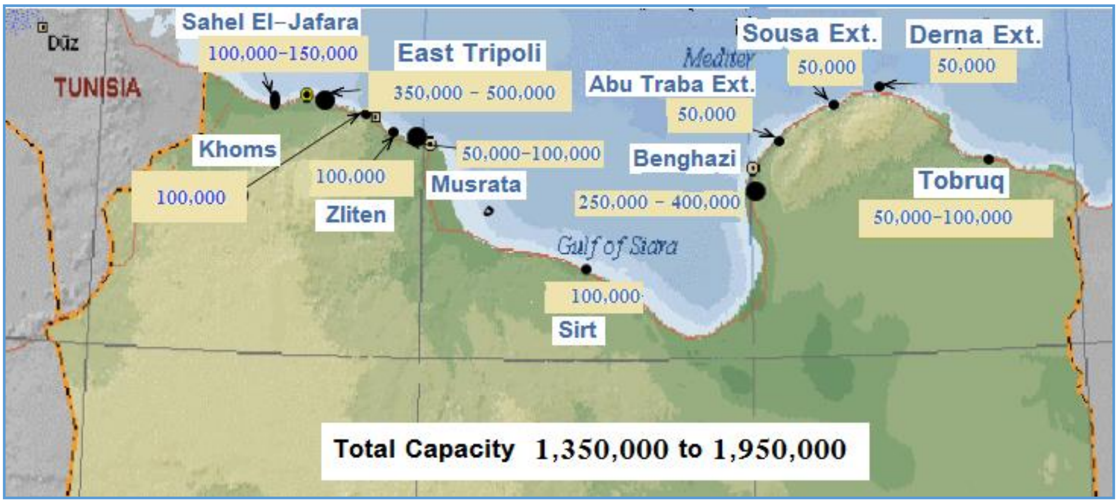

Figure 13: Future planned installation of Desalination plants by GDC [15,20]

NOC is responsible for operating more than 74 desalination units with small and medium capacity and different technologies as shown in Table 3 [24]. The total capacity is 90,510 m^3/day, and the expected future installation of the desalination units will increase this by 18 m^3/day. Thermal desalination processes will be suitable for sites near the sea, where there is the availability of steam for producing water in large volumes, whereas, non-thermal processes are more suited to inshore where electrical power is available and water is required in moderate or small volumes.

Table 3: Desalination units in oil and gas sector of Libya, 2013 [24]

Company	**No. of units**			**TVC**	**RO**	**Others (MED, ED)**	**Old/New Units Start Date**	**Current Total Production (m^3/day)**	**Future Installations (m^3/day)**
		MSF-BR	MSF-OT						
SOC	19	7	2	3	7		1964/1989	22,708	RO (7,920
RASCO	5	5					1983/1997	40,000	MSF-OT (8,000)
AGOCO	3			2	1		1999	750	
ARC	8		5	3			1974/2004	5,500	RO (1000)
Eni Oil	16				5	11	1982/2005	4,500	RO (288)
Eni Gas	3	3					2004	15,840	
Zuetina	12				7	5	1964/2004	532	RO (48)
VEBA	8				7	1	1986/2005	680	2 RO (360 per unit)
Total	74	15	7	8	27	17	1964/2005	90,510	

2.4.2 Desalination using renewable energy in Libya

The experience of solar desalination in Libya doesn't exceed much beyond some theoretical studies and small pilot projects. Many theoretical and experimental studies have been conducted to evaluate the performance and the economics of simple active or passive solar stills [25,26,27,28,29,30,31] and solar stills with multi-stages [32,33]. This kind of technology is very simple in design and manufacturing, but has a very low productivity. For example, a locally made solar still coupled with flat plate collector produces 6.6 l/m^2/da [25], whereas solar still with multi-stages produces 20 l/m^2/day. [33]

A techno-economic feasibility study is being conducted by GECOL and a consulting consortium of experts from ZSW, DEWI and LI to manage the implementation of an experimental research facility for Sea Water Reverse Osmosis desalination powered from Renewable Energy Sources (SWRO+RES) at the coastal village of Ras Ejder located on the border between Libya and Tunisia. The capacity of the suggested Reverse Osmosis (RO) desalination plant is 300 m^3/day. Both wind energy conversion (WEC) and photovoltaic power generation (PV) will be integrated into a grid connected power supply to the plant. The average salinity of sea water at the site is 42,000 ppm TDS. The annual irradiance of 1829 kWh/m^2 falls on a surface tilted at 25° from horizontal to South thus making a good solar source for photovoltaic power generation. The annual average wind velocity is 4.4 m/s at 10 m height, which is not very advantageous for wind energy conversion to power. The expected nominal power load for the operation of the RO desalination system is 60 kW (net power after recovery), the solar PV system is designed for 50 kW peak, and the WEC for 275 kW nominal output. The WEC configuration aims at more than 80% reduction of the annual grid power consumption. This is predicted to increase the Levelised Water Cost (LWC) by not more than 45% compared to the grid-power-only solution with its very low electricity cost of 3.2 Euro/kWh [34,35].

The experience of the Centre for Solar Energy Research and Studies (CSESR) in solar desalination started with the solar pond project in the early 1990s. A 5 m^3/day Multi-Stage Flashing (MSF) desalination unit with 14 stages is coupled with the solar pond as shown in Figure 14. The general view and technical specifications of the desalination plant are shown in Figure 15. The plant can work over a wide temperature range of low grade thermal energy input without loss of efficiency. The maximum design working temperature is 80 °C, and the preferable range of operation is between 70 – 80 °C.

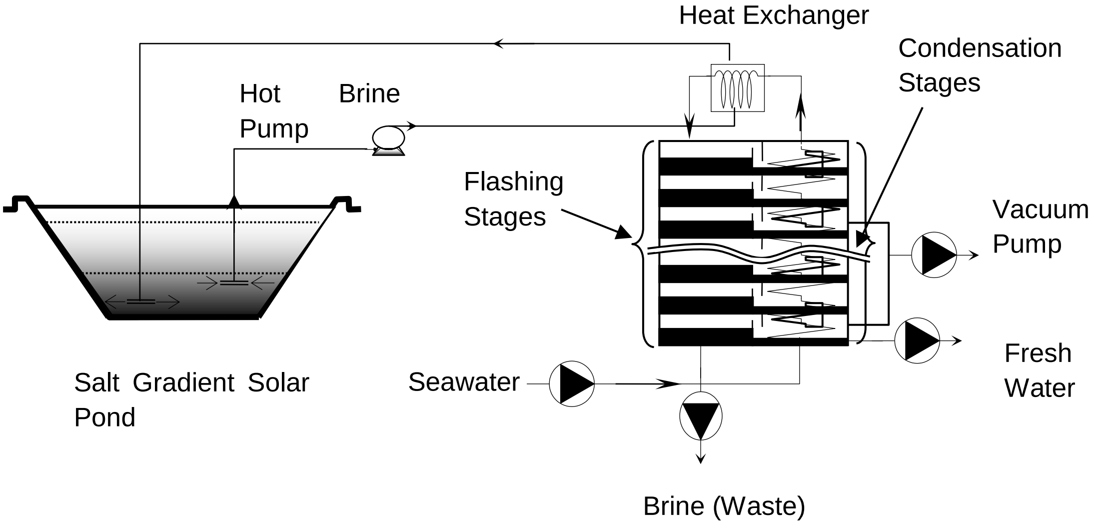

Figure 14: Schematic drawing of MSF Desalination Unit coupled with the Tajoura Experimental Solar Pond (TESP).

Item	value
Average daily production of fresh water	5 m^3/day ($0.208m^3$/hr)
Max working temperature	80 ° C
Sea water temperature	20 ° C
Thermal energy consumption	15.6 kW
specific consumption of electric power	4.8 kWh/m^3
Rate of flow of sea water (nutrition and cooling)	2.3 m^3/hr
Flow rate of saline solution	2.1 m^3/hr
Concentration of the Mediterranean sea waters	35,000 ppm.
Specifications of desalinated water	< 100 ppm

Figure 15: A view of the MSF Desalination unit and its technical specification.

The Tajoura Experimental Solar Pond (TESP), Figure 16, is located to the east of Tripoli. It has a surface area of about 830 m^2, and a depth of 2.5 m, coupled to an evaporative pond of 105 m^2 area, 1.5 m deep. The daily thermal energy supplied by the solar pond to the desalination unit at nominal operating conditions is about 375 kWh per day and at a temperature of about 70^{o}C. The desalination plant has worked for a long period of time with full capacity without affecting the stability of the pond.

Figure 16: General view of Tajoura's Experimental Solar Pond.

A project started at the end of 2013 to operate the existing MSF desalination unit by using vacuum tube collectors. 90 vacuum tube collectors of type DRC 10 with total area of 180 m^2, four storage tanks, five pumps, hydraulic pipes, safety and control equipment are used to run the project. Most of the civil engineering aspects of work at the site have been executed as shown in Figure 17. However, this project has stopped due to financial problems related to the political instability in the country. [36,37]

Figure 17: MSF desalination operated by vacuum tube collector project

2.5 Water Treatment

Figure 18: Water treatment plant

The production of fresh water is a significant problem for most of mankind, while the disposal of the result of the consumed water, which is sewage, could be an even bigger problem. However, the problem of sewage disposal might be a part of water problem solution. Currently, more than 30% of the water consumed in countries such as Jordan, Tunisia, Egypt, and Qatar is treated water. Therefore, Libya is employing the treatment of wastewater to fulfil a part of its water needs.

Since 1971, 73 wastewater treatment plants have been constructed in Libya with a total capacity of about 600,000 Mm^3/day and 6,000 km of sewage pipelines to cover only 17% of the population. Furthermore, as illustrated in

Figure 19, the total capacity still in service, in 2010, was about 154,000 Mm^3/day while the treated wastewater is 60.4 Mm^3/day. [15] in 2010.

At the beginning, the plan was to reuse 70% of the treated effluent for agricultural use, 20% for discharging into open areas (wadis and lakes) and 10% for discharging into the sea. Otherwise, in 2015, no wastewater was reused. [15]

Commonly, the wastewater treatment process is classified into four stages; the first is sedimentation where no product water could be used, the second and third contains biological, chemical treating and filtration. The product water from the second could be used for non-food crop irrigation and industrial use. The fourth stage could produce water for agricultural uses, human consumption and recharging of wells. The final stage includes nano-filtration and UV treatment where the resultant water could be utilized for drinking or food related manufacturing. The total cost of sanitation collection and treatment, in 2010, is expected to be 3.73 LYD/m^3. [14]

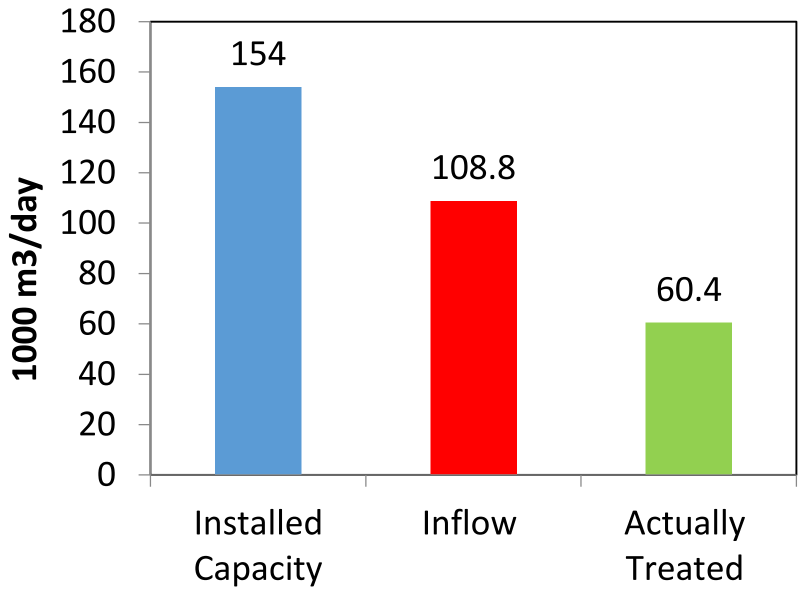

Figure 19: Operating Plants in 2010 (1000 m^3/day) [15]

Currently, most of the wastewater treatment plants mentioned above are out of service, with only 9 out of more than 70 plants still in service, due to some technical and economic reasons. In addition, increasing the capacity of treated water requires increasing the sewage network, whereas 70% of waste water seeps back into ground, while 5.4 Mm^3/year is collected by trucks rather than the sewage pipe network. Therefore, by developing the sub structural sanitation system and, providing financial support, qualified staff and spare parts could enhance the proportion of reused water in consumption. [15]

3 The feasibility of solar desalination

Using solar energy as a driving power in desalination processes represents one of the most promising solutions to tackle the issue of potable water. Solar desalination is a feasible solution, especially for arid and remote areas where electricity and oil supply are limited. These regions are blessed with a high rate of solar radiation. Solar desalination is not only clean and sustainable, compared with conventional energy sources, but is also flexible to use solar radiation directly as thermal power or convert it to electricity using PV technology. However, the intermittent nature of solar radiation leads to restricting the productivity of freshwater from solar desalination processes, representing the main disadvantage of these units [38, 39].

3.1 Overview of solar desalination systems

Solar water desalination refers to plants which use solar energy to drive the desalination processes. These systems could be classified based on the method of harnessing solar energy, into two categories: direct and indirect solar desalination systems.

Direct solar desalination comprises solar distillation systems or solar stills. In this category, the desalination unit is completely operated by thermal solar energy independently of any other source of energy. The operation principle is based on evaporation and condensation phenomena which simulates the rain formation process which occurs naturally in the environment. In solar stills, the saline water enters a closed container covered by a glass surface. Solar radiation passes through the glass cover to heat the water and generates vapour. Consequently, this vapour condenses on the internal surface of the glass cover leaving all contaminates, microbes and salt behind in the container. Finally, the condensed freshwater is collected and stored in another clean container [40]. In these systems, the desalination process occurs directly in the same unit. The solar distillation systems can be “passive” and operate without any assistance from an external source of heat or “active” which is a passive system supported by an external heater to enhance the evaporation process [40]. The solar stills are simple, cheap, easy to install and do not need a high rate of solar radiation. The productivity of solar stills is about 4–6 litre/m^2/day which makes it more economic to provide fresh water for families and small communities [41-43].

The indirect solar desalination systems consist of two separate units: a solar collection or solar field unit to receive solar radiation and transform it into thermal energy or electricity and the second unit, a desalination system which is operated using the energy absorbed by the first unit. There are different designs and configurations which include solar humidification and dehumidification processes and solar assisted conventional desalination systems. These systems can be phase change or membranes systems and they are more economic in large scale operation. The major commercial solar desalination processes will be discussed here. The effectiveness and reliability of indirect solar desalination systems depends on two factors including availability of solar radiation and selecting the most appropriate integration between solar systems and desalination technology in terms of both cost and energy performance at a specific location [44].

3.1.1 Solar humidification and dehumidification desalination (SHDD)

The working fluid in these systems is air and the operational principle depends on the capability of dry air to carry a significant amount of water vapour, and on increasing this capability by elevating the temperature of the air using solar energy. Generally, when dry air comes into contact with seawater in the evaporator, it will be saturated by a certain quantity of vapour. Then, this humid air is circulated naturally or forcefully to pass over the condenser, a cool surface, and thus extracting the freshwater. The SHDD systems conventionally consists of a humidification unit, usually it is a solar collector, and a dehumidification unit. There is a stream of air between them to force the water vapour towards the condensation area. These systems could be open water/closed air cycle in which the air is circulated between a humidifier and a condenser or closed water/open air cycle in which the water is circulated while the air enters and leaves the system [45, 46].

3.1.2 Solar Multi Stage Flash (MSF) desalination systems

The MSF desalination is the most mature and widely applied desalination technology which has high productivity and is economically competent. The MSF technique is based on the flash process of hot saline water to produce vapour. In this technology the saline water, after being heated, is rapidly discharged into a number of stages with pressures gradually reducing from stage to stage. This sudden decrease in pressure and the relatively high temperature results in fast evaporation, flash, of a fraction of the hot water. Heat exchangers are used in this method to condensate the vapour and produce freshwater. The heat released during condensation is used to preheat the saline water. The thermal energy produced by concentrating solar power (CSP) can be a feasible option to drive MSF process independently or hybrid with electricity generation. Forecasting studies expect a continuing increase in CSP technology and in parallel with the negatives associated with the use of fossil fuel, make solar MSF desalination an economic alternative compared with conventional systems [47, 48].

3.1.3 Solar Multiple Effect Distillation (MED) systems

The MED systems operate on the principle of reducing the chamber pressure at each successive stage, allowing the feed water to undergo multiple boilings without having to supply additional heat after the first stage. In this unit, steam is fed into a series of tubes, where it condenses and heats the surface of the tubes and acts as a heat-transfer surface to evaporate saline water on the other side. The energy used for evaporation of the saline water is the heat of condensation of the steam in the tube. The evaporated saline water is fed into the next, lower-pressure stage where it condenses to fresh-water product, while giving up its heat to evaporate a portion of the remaining seawater feed. The solar MED system is becoming more commercialized due to its reliability and cost compatibility with conventional systems. It has been reported that integration between a 30,000-40,000 m^2 area solar field with MED technology can produce up to 100,000 tons of fresh water per year with competitive cost [40, 47, 48].

3.1.4 Solar Reverse Osmosis (RO) desalination

The operation principle of the reverse osmosis process (RO) is based on separation of water by a semi-permeable membrane with the saline water on one side and freshwater on the other. The saline water must be pressurized to exceed the natural reverse osmosis pressure which is about 50-80 bars to produce a feasible amount of freshwater. At this pressure, the saline water starts to pass through the membrane leaving the concentrated brine behind on the saline water side [2]. The energy required to run a RO plant is mainly needed to drive high pressure pumps and create sufficient pressure. This energy could be produced using PV technology or thermally using the solar Rankin cycle. Small scale RO desalination powered by PV technology is a more common form of integration. However, it has been reported that integration between CSP and RO is more efficient than the integration of CSP with MED [48, 49].

3.2 Solar potential in Libya

Libya’s location and solar radiation resources are highly suited to the utilization of solar energy. Libya is situated in the centre of North Africa between latitudes 19° to 34° North and longitudes 9° to 26° East. Most of the country area located in the heart of the Sunbelt and around 88% of Libya’s land area is desert. The Sahara Desert covers the entire range of Libya's land. It is situated between longitude 11^o 44’ to 23^o 58’ East and a latitude range of 24^o 17’ through to 30^o 3’ North [50, 51].

The country is classified as wealthy with respect to the solar radiation resources. The distribution map of average annual Global Horizontal Irradiation (GHI) and Direct Normal Irradiation (DNI) cross the country are illustrated in Figure 20 and Figure 21 respectively. This data was recorded and averaged during the period of 1994 – 2010 by SolarGIS [52, 53]. It can be observed that, the average annual GHI is in the range of 2000 kWh/m^2/year in the North regions and over 2600 kWh/m^2/year in the Southern regions. The average annual DNI is varying between about 1900 kWh/m^2/year on the coastal region and 2500 kWh/m^2/year at the South [52, 54].

In addition, information about the insolation sky clearness index and average number of sunshine hours is presented by NASA Surface Meteorology and Solar Energy database. The monthly average sky clearness index for ten different locations in Libya is demonstrated in Figure 22. Al-Kufrah site has the maximum clearness index of 0.68 and the minimum at Tripoli of 0.57. Also, the average number of sunshine hours cross the country is more than 3500 hours per year [54, 55].

CSP plants can be considered economically valuable only for locations with DNI above 1800 kWh/m^2/year [56, 57]. Based on this fact, CSP technology is a very promising choice for electricity generation in Libya (depending on the intensity and quality of solar radiation available).

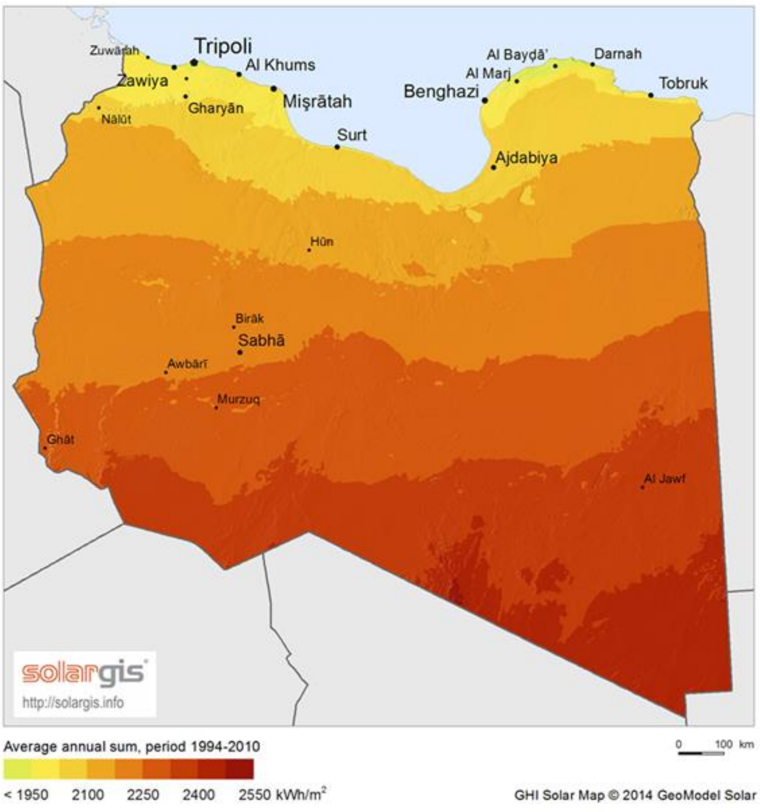

Figure 20: Average global horizontal irradiation (GHI) in Libya [52]

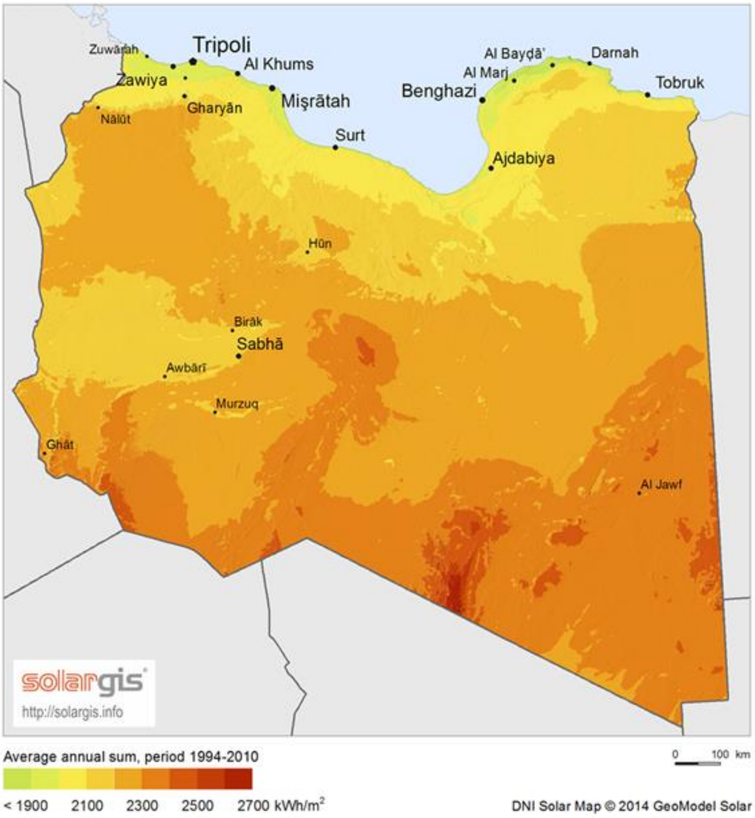

Figure 21: Average direct normal irradiation (DNI) in Libya [53]

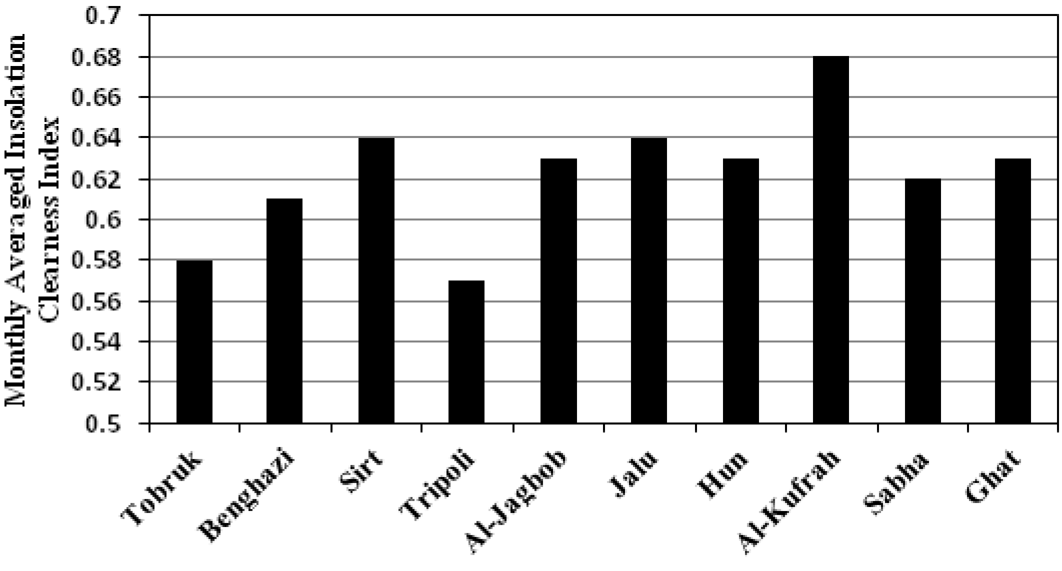

Figure 22: Monthly average insolation clearness index over various sites in Libya [25]

4 Simulation of large-scale solar desalination plant at the North of Libya

To evaluate the performance of solar desalination in Libya, a 50 MW CSP plant integrated with MED systems is proposed to operate under North Libyan climate conditions. The 50 MW parabolic trough hybrid operation (electricity and desalination) plant has been chosen, because the parabolic trough is the most commercial and mature CSP technology. In addition to that, most of these technologies have a capacity of 50 MW whether it is individual or combined with other plants at the same location such as Andasol 1 to 3 and Extrasol 1 to 3 [58].

4.1 Site Location and weather data

The southern part of the country has higher solar resources compared with the northern coast. The typical northern weather of the country is chosen to analyze the performance of the CSP-MED plant and the site selected for conducting the study is Tajoura city, where the Centre for Solar Energy Research and Studies (CSESR) is located (32^{o} 48'- 130^{o} 24'). The city is in a coastal region, nearly 20 km east of the capital of Libya, Tripoli.

The performance of CSP-MED plants strongly depends on the meteorological conditions at the specific location of the plant. For instance, the direct solar irradiance DNI has direct influence on the efficiency of the CSP plant. Other environmental factors such as ambient temperature and wind speed, have an effect on heat losses from the different systems of the CSP plant. The CSESR has a weather station installed at the proposed site collecting solar radiation data and 12 weather parameters. Figure 23 shows the main measuring facilities for the installed meteorological station. The weather station has the following equipment:

- Kipp & Zonen ―SOLYS 2‖ two-axis sun tracker.
- Integrated global positioning system ―GPS‖.
- Kipp & Zonen pyranometers for solar radiation measurements
- Kipp & Zonen CSD 3 sunshine duration sensor.
- Anemometers to measure wind speed and direction sensor.
- Hygrometer to measure relative humidity.
- Temperature sensors to measure ambient temperature.
- Pressure sensors to measure atmospheric pressure.

Figure 23: Meteorological station installed at CSERS in Tajoura city

4.2 Description of the proposed plant and method of simulation

The Andasol-1 parabolic trough plant, located in Spain, is used as a reference plant in this study. The technical design parameters of Andasol-1 are utilized for the proposed plant in Libya as shown in Table 4. The solar field is based on the Euro Trough ET150 solar collector integrated with the capability for 8 hours thermal energy storage. The ET150 solar collectors are oriented in the North-South direction with heat transfer fluid Dowthern A with temperatures of 293^{o}C at the inlet and 393^{o}C at outlet. For the power block, a simple Rankine cycle is used and steam is extracted after a high-pressure turbine to feed a six stage MED desalination system.

The analysis of the performance of the proposed plant has been conducted using two separate pieces of software. System Advisor Model (SAM) software is used to model solar field and thermal energy storage and was developed by National Renewable Energy Laboratory (NREL). It has the capability of simulating different renewable energy systems including parabolic trough power technology. Power block and desalination are modelled by the IPSpro package due to its powerful capabilities in energy and thermodynamic process application. Output data from SAM is used as input information to IPSpro model. A schematic diagram of power block and 6 stage MED desalination is shown in Figure 24.

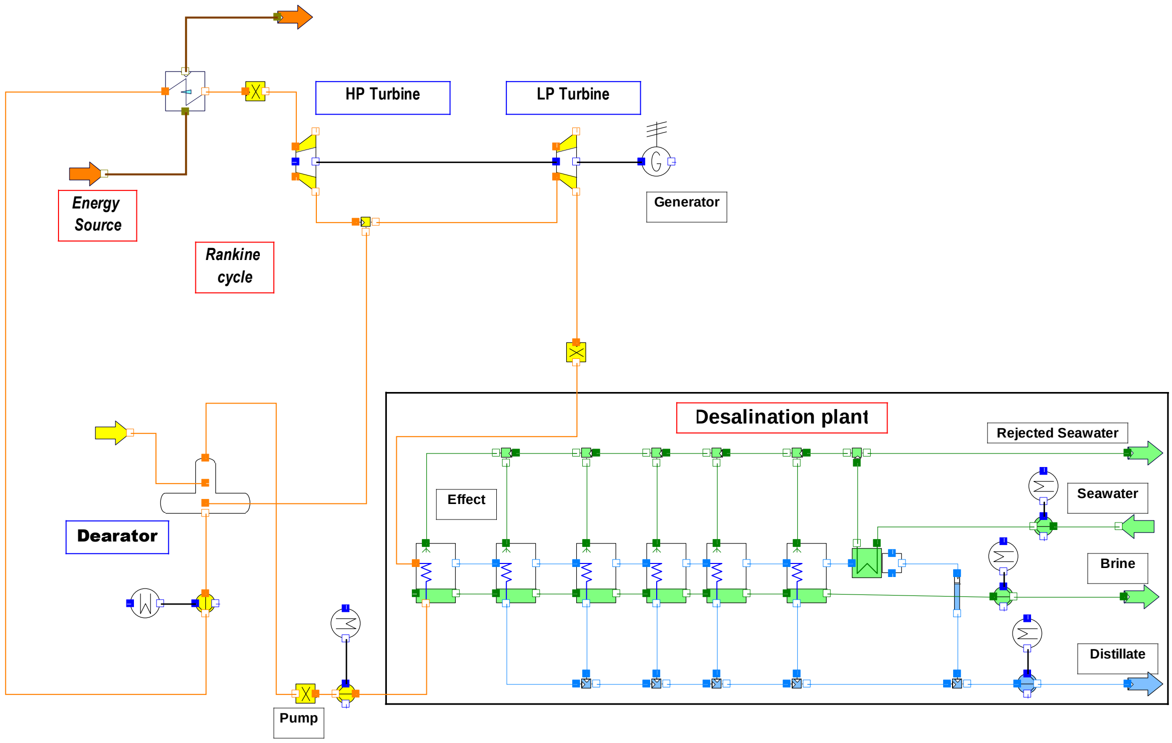

Figure 24: IPSpro schematic diagram of the proposed plant

Design parameters of the proposed plant are shown in Table 4.

Table 4: Design parameters of the proposed CSP-MED plant

Solar field		Rankin – MED	
Characteristics	**Value**	**Characteristics**	**Value**
Total plant capacity	50 MWe	Evaporation pressure	70 bar
Solar field aperture area	510120 m^2	HP Turbine outlet pressure	1.5 bar
Length of one collector	150 m	LP Turbine outlet pressure	0.386 bar
Aperture width of the collector	5.75 m	Desalination outlet temperature	75 ^oC
Optical efficiency	0.85	Deaerator outlet temperature	80 ^oC
Number of loops	156	Seawater temperature	27 ^oC
Row spacing	15 m	Seawater salinity	0.03845 pp
HTF type	Dowtherm A	Turbine isentropic efficiency	100 %
Absorber tube inner diameter	0.066 m	Turbine mechanical efficiency	80 %
Absorber tube outer diameter	0.07 m	Pump mechanical efficiency	70 %
Design loop inlet temperature	293 ^oC	Generator mechanical efficiency	98 %
Design loop outlet temperature	393 ^oC	Generator electrical efficiency	98 %
Full load hours of TES	7.5 hours	Motor electrical efficiency	90 %
Storage fluid	Molten salt	Motor mechanical efficiency	64 %
		Number of stages of the MED unit	6

4.3 Results and discussions regarding the simulation of the proposed plant

This section discusses the simulation results of the proposed plant. Variations of energy, power and fresh water flow between different components during operation of the proposed plant are presented. The annual performance and one representative day of two seasons, summer and winter, were chosen to explore the performance of the plant. These two seasons represent the maximum and minimum solar DNI which theoretically lead to highest and lowest performance of the plant. The types of energy flows considered at different stages of the plant in this analysis are summarized as:

- Q_{in} is the total solar thermal power incident on the solar field (W)
- Q_{st} is the thermal energy inside thermal energy storage (W)
- W_{net} is the net electric energy produced by the plant (W)
- M_f is hourly rate of fresh water produced (l/hr)

Figure 25 describes the performance of the plant during a typical summer day. The total thermal solar energy incidents on the concentrators Q_{dni} is above the level of 350 MW between 9:00 and 16:00 and reaches the maximum of 450 MW at midday. The variation of the thermal energy stored Q_{st} shows the difference between charging and discharge periods inside thermal energy storage. Q_{st} is positive when the solar field is charging thermal energy storage by thermal energy. Oppositely, Q_{st} is negative during the discharge of this amount of energy to the power block to produce steam. The Q_{st} is varying between 150 MW and -150 MW in which the discharge lasts for about 8 hours between 18:00 to 2:00 on the next day. The rest of the period to the sunrise of the next day should be covered by a backup boiler with a duration of about 4 hours. The thermal energy storage is stabilizing the amount of energy entering the power cycle. The net electrical energy production W_{net} starts at 7:00 above 35 MW and stays stable until 2:00 on the next day. Then the power produced stops until the system returns to full production after sunrise of the next day. Generally, the plant produces electricity at full load (35 MW) for about 19 hr. Fresh water productivity starts to coincide with the electricity, with a rate of 750 m^3/hr from 7:00 to 2:00 before the productivity stop until the next day.

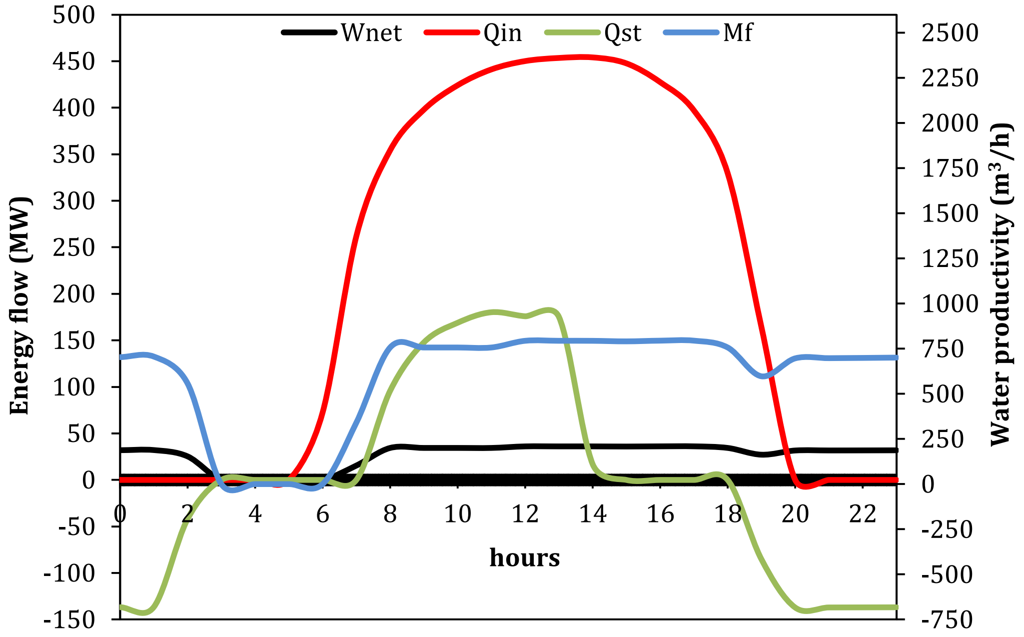

Figure 25: The plant performance during a typical summer day.

During the winter, Figure 26, the plant shows an intermittent and irregular performance. Even though the Q_{in} reaches the maximum value of about 420 MW around the noon, it has a significant value, above 350 MW, for the relatively short time of about 5 hours. Combined factors including low ambient temperature, high wind speed, a low solar incident angle in this season and intermittency in the Q_{in}, leads to a significant reduction in the thermal energy produced by the solar field in which it does not exceed 150 MW for most of the season. In addition, there is not enough thermal energy to be stored (Q_{st}) which restricts the plant’s ability to generate electricity after the sunset. The net electricity generation (W_{net}) and productivity (M_f) is limited only during the day time for a period of not more than 6 to 7 hours. During this period, the W_{net} average production is about 15 MW while productivity is 750 m^3/hr.

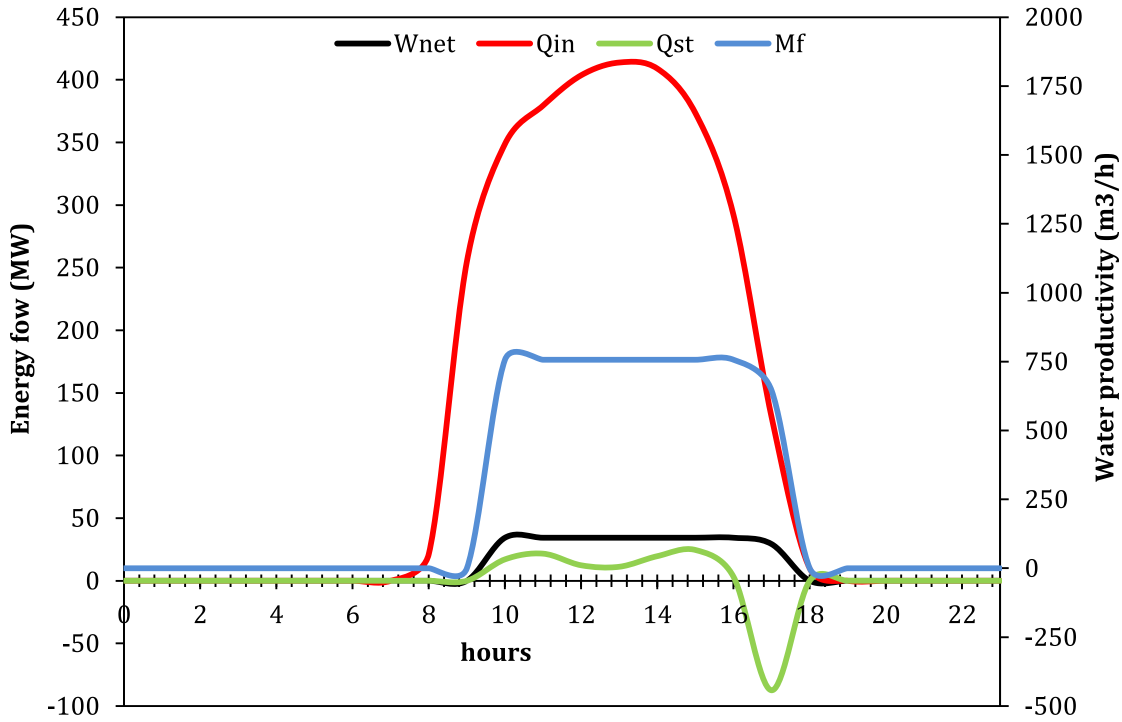

Figure 26: The plant performance during typical winter day.

The monthly net electric power and fresh water produced by the proposed plant is described in Figure 27. This energy, which is ready to be uploaded onto the grid, reaches the maximum during summer season. The monthly electric production exceeds the value of 10 GWh for six months from April to September. The total amount of fresh water produced is 0.43 Mm^3 in July and below 0.1 Mm^3 in December. The minimum production occurs during the winter months due to the reasons described previously and because of the low sun elevation angle receiving by single-axis tracking of the parabolic trough configuration.

Figure 28 presents the average electric, overall efficiencies and GOR of the proposed plant. (The GOR is the ratio between the fresh water productivity mass flow and steam flow rate input to desalination system). It can be observed that the maximum electric and overall efficiencies are 20% and 35% respectively. These two efficiencies vary from a minimum during the winter season, due to the significant increase in losses, and reaches a maximum in summer supported by the high potential of solar DNI radiation then. The average GOR of the plant is 2.5.

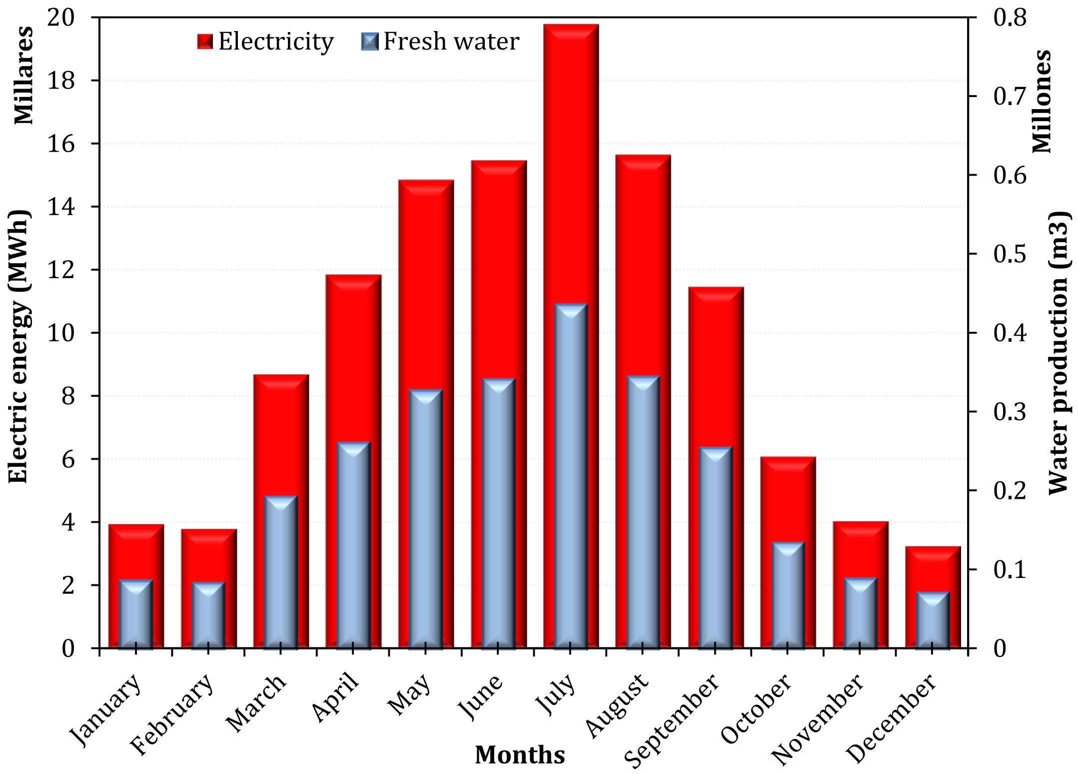

Figure 27: Monthly electrical net power and fresh water generated from the proposed plant.

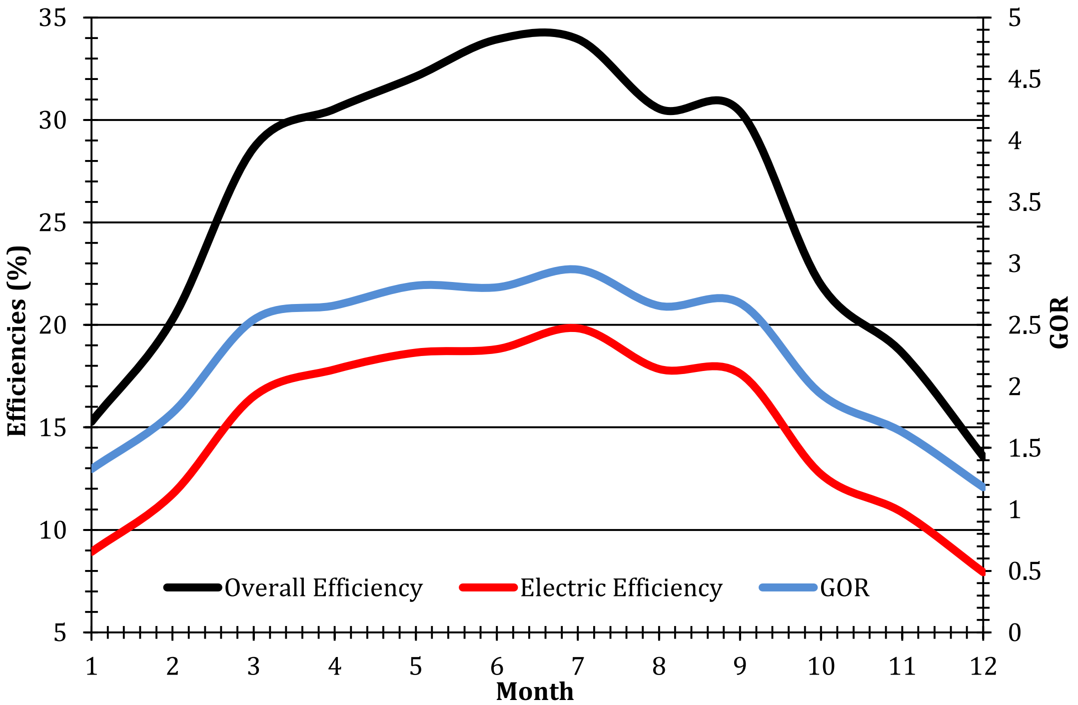

Figure 28: Efficiency and GOR of the proposed plant during the year

5 Economics of solar desalination systems

The cost of the fresh water produced from solar energy is strongly associated with the amount of useful energy generated from this technology. Regardless of the development in solar technologies and the free cost of solar radiation, the capital cost of these systems is still very high, leading to expensive fresh water production. The continuing progress and development of solar systems are expected to achieve a promising reduction in capital costs in the near future, which should make fresh water production more economic by this method.

Table 5 presents the energy demand and fresh water cost attributed to the integration of different commercial solar desalination systems.

Table 5 Energy consumption and water production cost of solar desalination systems [59]

Solar desalination process	Capacity (m^3/day)	Energy consumption (kWh/m^3)		Fresh water cost (\$/m^3)
		Thermal	Electrical	
Solar HD	1-100	29.6	1.5	2.6-6.5
Solar pond/MED	20,000-200,000	12.4-24.1	2-3	0.71-0.89
Solar pond/RO	20,000-200,000	-----	4-6	0.66-0.77
Solar CSP/MED	>5000	12.4-24.1	2-3	2.4-2.8
Solar PV/RO	<100	------	4-6	11.7-15.6

6 Conclusion

Water scarcity is a worldwide issue. Most of our fresh water is not located in readily accessible places. With a rising population and increasing demands as the standard of living rises in many areas, this presents a huge problem.

Desalination processes are capable of converting saline, brackish and even wastewater sources into potable water, water that is low in TDS or water that is of sufficient quality for agricultural uses. However, desalination is energy intensive, making alternatives to the traditional oil and gas driven processes highly desirable.

Libya represents a sparsely populated state, with 6 million people covering an area of about 1.8 Mkm^2. Most of these live in the North. It has a mostly semi-arid to arid climate and is in fact, one of the driest regions in the world, with very low precipitation rates which vary in intensity from year to year and a limited fresh water supply. It already meets some of its demand by seawater desalination and transferring water from source to regions of scarcity but this is energy consuming. However, the population and demand for water is growing and annual water deficits have been estimated variously between 1.2 to 4.3 km^3 for the years 2020-2030 [10-13].

Libya has the distinct advantage of having a high DNI (varying from 1900-2500 kWh/m^2/year across the country) but, as yet, has limited experience of solar desalination. Currently, its solar desalination activities are mostly theoretical studies and small pilot projects.

This report has discussed how water resources are located in Libya (predominantly as groundwater) and explains how some of the problems of relocating it to where it is most needed is currently addressed. For example, the Great Man-Made River project consisting of 4500km of pipeline delivers fresh water from aquifers in the Sahara to the populous North coast. Unfortunately, the main source for this river is not being recharged due to low rainfall. Although Libya has a 1900km long coastline, historically water transference was selected as a cheaper option to desalination. Subsequently, desalination costs have decreased, so this no longer holds true.

Existing conventional desalination in Libya consists mostly of thermal processes (63%) with the remainder being membrane processes. These plants currently produce about 62Mm^3 annually. In 2010, the average energy consumption to produce 15.2Mm^3 was 86,048MWh (Table 1, p7) i.e. 0.006MWh/m^3 [16].

A simulation of a large-scale (50 MW) parabolic trough type solar desal plant (MED) in the coastal city of Tajoura in North Libya is detailed in this report. This indicates that in the summer that the plant produces electricity at full load (35MW) for about 19 hours per day and fresh water production occurs at a rate of 750m^3/hr over a 7-hour period per day. In the winter, the average net electricity production drops to 15MW for about 6 to 7 hours per day while productivity during those hours is about $750 m^3/hr$. The average energy consumption per volume of water produced is approximately $0.05\ MWh/m^3$ (calculated from fig. 27)

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