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The CSP Today Industrial Applications Guide: Desalination and Enhanced Oil Recovery, has been published in conjunction with the exciting launch of CSP Today Sevilla 2013, taking place on 12-13 November in Sevilla.

For more details on CSP Today Sevilla 2013 please visit: www.csptoday.com/sevilla
Overview

In the first part of the CSP Today Industrial Applications series, the potential to integrate concentrated solar power with the mining industry was examined.

In this edition, two exciting opportunities are under consideration: Enhanced Oil Recovery (EOR) and desalination. Through the guide you will see where and how this integration process makes sense, as well as case studies on where it has already been done before.

We hope you find the guide useful - if you have any questions please contact us.

CSP Today

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1.0 CSP and the Desalination Industry

Fresh water is a limited commodity which, with a limited supply and availability, requires wise management to meet globally increasing demand. While future fresh water supply is becoming a concern in both the developed and developing world, the situation is particularly severe in the MENA countries. There, its scarcity makes it an invaluable resource from the onset, a situation that is aggravated by the region’s changing demography, industry and life standards.

1.1. Potential markets – MENA region

The MENA region is one of the most water-stressed parts of the world, and over the last 30 years the per-capita fresh water availability has been reduced by half largely due to rapid population growth and over-exploitation of the natural water resource. Indeed, according to World Bank, 14 of the world's top 20 water-scarce countries are located in the MENA region. In many countries throughout the MENA region large amounts of freshwater are currently produced by desalinating seawater, using expensive fossil fuel energy as the main energy source. In most cases, fuel is supplied from the country's own oil and gas resources. The displaced commodity could instead be used for more valuable processes, exported at elevated prices or preserved. In countries where fossil fuels must be imported, desalination is an expensive process that is highly susceptible to fuel price volatility. In any case, burning fuel for fresh water production is unlikely to be sustainable in the mid- to long-term, when alternative energy sources such as solar energy are increasingly utilized.

The unique properties of CSP along with the excellent solar resource found in the MENA region, offer a huge opportunity for CSP technologies to provide reliable fresh water production, either through thermal processes (Multi-Effect Distillation) or through electricity driven processes (Multi-Stage Flash), replacing the use of fossil fuels.

Fresh water demand management in the MENA region is particularly important due to the scarcity of the supply, the demographic growth (2-3% annually, a trend expected to be upheld up to 2050) and the changing standards of living where more water is consumed. Consequently, enormous pressure has resulted on water resources, creating unbalances and shortages and ultimately, the potential for degradation in water resource quality. Indeed, for the 5% of the world population living in the region, less than 1% of the world’s fresh water supply is available. This inevitably impacts the average annual per capita available water resource in the MENA region to 1250 m³/person/year (1/3rd of the water available per capita in Asia and 1/6th of that available in Africa) [9].

In this context, securing water supply is a priority for these nations as can be seen by the fact that specific or partial Ministries are usually dedicated to water management.

The situation is exacerbated in some poor water countries of the MENA region, where water availability per capita resides far below the 1000 m³/person/year threshold. In fact, only a few countries in the MENA region are above this threshold.

Figure 1.1: Water Consumption Worldwide

![Water Consumption Worldwide Chart](chart.png)
As previously stated, the situation is aggravated by the fact that population growth is expected to see a constant boom in the future. The current population is expected to double in the next 50 years (reaching 700 million by 2050), which will impose a greater pressure on water supply. MENA economies are growing at a high rate and are reaching standards of living similar to most of the developed countries where large amounts of water are consumed. As a consequence water demand will grow considerably in the region, increasing the over-exploitation of limited natural ground water available already seen today, depleting the resources and increasing the water deficits that will have to be covered with desalinated water.

With the arid climate intrinsic to the region, water scarcity in the MENA region is expected to grow from 277,000 Mm³/yr in 2010 to 450,000 Mm³/yr in 2050 (Ref: New Mexico Water Resources Research Institute). As a result, the pursuit of sustainable alternative fresh water resource becomes evident and essential in order to bridge the projected water gap. Sustainable fresh water resource exploitation must have the following objectives:

- Economic Efficiency
- Social Development and Social Equity
- Environmental Protection
- Sustainability of Water Supply and Services
- Political Acceptability

To further demonstrate the relevance of CSP desalination for the MENA countries, a country-wide breakdown of the water deficit is shown in Figure 1.4, along with the CSP desalination potential proposed by the AQUA-CSP project from DLR to address this imminent fresh water crisis (Figure 3.5). Based on the results of this study, Egypt is the country that offers a greatest potential for CSP desalination with an estimated fresh water generation of 65,000 Mm³/yr by 2050 followed by Saudi Arabia with a 32,000 Mm³/yr of
fresh water by 2050. Other countries such as Yemen, Syria, Libya and UAE also offer large potential to deploy CSP desalination facilities.

1.2. Integration of CSP Technologies

There are different desalination technologies being deployed worldwide that have achieved commercial status with proven track record. These technologies produce fresh water by two different processes - evaporation and separation through membranes, using as the driving force thermal energy and mechanical power (electrical power) respectively.

Three technologies are primarily utilized for seawater desalination: multi effect distillation (MED), reverse osmosis (RO) and multi stage flash (MSF). The dominant technology is RO, accounting for 60% of the global capacity, followed by MSF with 27% and MED with 8%. Although these three technologies are mature and capable of producing large amounts of fresh water, the selection of the most suited desalination technology from a technical point of view will be based on the water production capacity, the energy consumption (both thermal and electric) and the seawater quality.

With a current worldwide sea water desalination capacity of 65 million m³/d, the desalination industry consumes around 75 TWh of electricity annually (which represents around 0.4% of the global electricity consumption). This is the equivalent to the electricity that would be generated by 500 Parabolic Trough plants with 50MW and 7 hours of storage, like those deployed in Spain, and representing a cumulative investment in excess of 120,000 million Euros. The global desalination capacity is expected to rapidly grow, with a forecasted electricity consumption of 122 TWh by 2030 in the MENA region alone. This will more than double current consumption and result in the need to add large amounts of new electricity generation capacity - in the range of thousands of MW (equivalent to more than 500 Parabolic Trough plants). Such figures highlight the conundrum facing the region, and the promising opportunities open to CSP technologies to displace

Table 1.1 Desalination technologies

<table>
<thead>
<tr>
<th>Process</th>
<th>Evaporation</th>
<th>Membrane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal</td>
<td>Multi Stage Flash (MSF)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Multi effect Distillation (MED)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Solar Stills</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Multi effect Humidification (MEH)</td>
<td></td>
</tr>
<tr>
<td>Mechanical</td>
<td>Mechanical Vapor Compression (MVC)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vacuum Membrane Distillation (VMD)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Electro Dialysis (ED)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reverse Osmosis (RO)</td>
</tr>
</tbody>
</table>
fossil fuels in this industry.

The integration of CSP technologies with desalination processes offers particular benefits if it is combined with thermal energy storage. This can be achieved using three different design solutions which combine electricity and thermal energy generation via either thermal or membrane separation processes:

1. Use CSP technologies to generate electricity as a conventional CSP power plant to supply the electricity consumption of the desalination process. This is suitable for a RO process.
2. Use CSP technologies to generate steam to supply the thermal energy consumption of the desalination process. This is suitable for a MED/MSF process.
3. Use CSP technologies to generate both electricity and thermal energy (combined heat and power generation) to supply both the thermal and electricity consumption of the desalination process. This is suitable for a MED/MSF process.

In the case of a thermally driven process, the advantages of the MED technology over MSF lie in the lower thermal and electricity consumption, lower investment cost and the capability to be operated at variable load (which matches with the intermittent nature of solar energy without storage). For these reasons, MED is more suitable for integration with large-scale CSP desalination projects.

Although the integration of CSP technologies into a desalination plant offers great advantages, there are some challenges that must be taken into account:

- In order to be cost effective, CSP plants must be located in the vicinity of the desalination facility, i.e. close to the coast with the associated consequences:
  - Problems with materials due to a high saline atmosphere and potential sand erosion. This might lead to higher O&M costs.
  - Performance problems due to a reduced DNI (potentially more cloudy conditions), high aerosol load, high humidity and sand suspension.

For RO facilities, the CSP plant could be located inland although long transmission lines may be required unless power generation and consumption are decoupled; therefore using the CSP plant as a

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**Table 1.2 Key parameters of desalination technologies**

<table>
<thead>
<tr>
<th>Technology</th>
<th>Concentrate Temperature (°C)</th>
<th>Electricity Consumption (kWh/m³)</th>
<th>Thermal Consumption (MJ/m³)</th>
<th>Typical Production (m³/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MED</td>
<td>60 to 75</td>
<td>1.5 to 2.5</td>
<td>150 to 200</td>
<td>100,000</td>
</tr>
<tr>
<td>RO</td>
<td>&lt;45</td>
<td>3.5 to 5.0</td>
<td>-</td>
<td>200,000</td>
</tr>
<tr>
<td>MSF</td>
<td>90 to 120</td>
<td>2.5 to 3.5</td>
<td>250 to 300</td>
<td>90,000</td>
</tr>
</tbody>
</table>

**Figure 1.6: Technical concepts for integrating CSP into desalination plants [9]**

- **Heat only**
  - Solar field
  - Storage
  - Grid
  - Fuel
  - MED
  - Water
  - Electricity

- **Electricity only**
  - Solar field
  - Storage
  - CSP Power Plant
  - Fuel
  - RO
  - Water
  - Electricity

- **Combined heat and power**
  - Solar field
  - Storage
  - CSP Power Plant
  - Fuel
  - Heat
  - MED
  - Water
  - Electricity
conventional solar plant to inject electricity into the grid. In the case of MED/MSF, this is not possible as transporting steam over long distance is not a viable option.

- The low temperature required for MED/MSF technology is way below the temperature levels achieved with the current large scale CSP technologies. New designs will therefore need to be investigated and further developed for thermally driven concepts such as combined heat and power.

It should be noted that the cost of CSP for desalination has decreased over the years and resides currently between US$1.6 - US$2.1/m³ (the lower end using RO and the higher end using MED), and it is expected to keep decreasing to US$0.9/m³ by 2050.

### 1.3. Case study

While fresh water from CSP powered desalination remains a fairly new application for the industry, its potential is already being explored in multiple locations. The MENA countries facing an imminent fresh water crisis are on watch, as the solar resource available makes for CSP desalination a great match with the water resource conundrum.

Under the AQUA-CSP project from DLR [9], a reference plant utilizing a Linear Fresnel collector was investigated using both MED and RO technologies. The Linear Fresnel collector type was chosen owing to its best land usage efficiency, its lower weight and simple structure, easy integration to the environment and ease of cleaning, as well as lower wind loads.

In this study, 7 different sites (Aqaba, Agadir, Abu Dhabi, Malta, Al Khawkha, Gaza and Hurghada) were investigated with a target production of 24000m³/day with 21MW net power production. For this rated fresh water production capacity, the electricity required for desalination was found to vary between 2.11 MW and 5.60 MW, with a final grid power delivery of 20.9 to 25.2 MW. The CAPEX associated with such projects, using RO, was found to be €76.4M while the same throughput using MED required an investment of €84.9M as shown below.

Ultimately, the study revealed a cost of fresh water production from desalination, using RO in the MENA to be ~€1.55/m³, and ~€1.45/m³ using MED. By 2020, this same cost is expected to drop to ~€1.42/m³, and ~€1.24/m³ respectively.
2.0 CSP and the EOR Industry

Early in the lifecycle of an oil well, pressure in reservoirs will usually naturally push oil out and promote extraction. As the well is depleted, extraction rates are reduced and so the profitability. By the time the well reaches the end of its economically viable life, up to two thirds of a reservoir's oil can remain trapped and therefore un-extracted. With increasing oil viscosity, the fraction of untouched oil can be much higher. Advanced oil recovery technologies can help extraction companies boost oil field production and extend their lifecycle.

As an oil field ages, the decline in pressure and oil production require the injection of steam, chemicals or gas into the well. Injecting steam heats the oil in the reservoir, decreasing its viscosity and facilitating flow and extraction back to the surface, increasing productivity. Such a technique is known as enhanced oil recovery (EOR). Enhanced oil recovery is also referred to as improved oil recovery or tertiary oil recovery. Enhanced oil recovery is commonly used in mature fields where secondary techniques such as water flooding no longer produce economically viable quantities of oil. Using EOR, 30 to 60% or more of the reservoir's original oil can be extracted.

Present Use and Future of EOR
Used in the majority of oil extraction operations worldwide, enhanced oil recovery production has remained relatively level over the years, contributing to about 3 million oil barrels per day (MBPD), compared to approximately 85 million of barrels of daily oil production (~3.5% of the production coming from EOR techniques). The bulk of the EOR production is from thermal methods contributing an estimate of 2 million barrels of oil per day. In total, EOR could enable unlocking 300 billion more barrels of oil; enough to sustain production for an additional 10 years at today's extraction rates [11]. Additionally, the total world oil production using EOR is expected to rise to 20% by 2030 [12].

2.1. Potential markets – MENA region
Some of the biggest oil fields in the world are located in the Middle East and North Africa (MENA) region. Extraction for the countries part of the Organization of Petroleum Exporting Countries (OPEC) is still done in primary stage and there are additional reserves to support several decades. However, in non-OPEC Gulf countries, with continued uncontrolled oil exploitation, most of the oil wells have matured, and has therefore resulted in a decline in oil production. With the exception of Qatar, all Persian countries are running short of natural gas. As a result, non-OPEC countries are forced to use EOR techniques to sustain or increase their current oil production rates. OPEC countries are increasingly turning towards EOR, developing their expertise, ensuring energy security and more sustainable oil production practices.

Most of the OPEC countries are also blessed with moderate to good solar resources, and more precisely, with Direct Normal Irradiance (DNI) which is an integral requirement of CSP technology. The potential for using CSP for EOR in these regions is remarkable.

2.1.1. OPEC countries
Saudi Arabia is the world’s largest producer and exporter of crude-oil in the world. The country plans to produce more than 1 MBPD of heavy oil using EOR by the year 2030 [13]. Saudi Aramco is currently evaluating the use of CO2 injection and plans a series of pilot programs in mature fields like Ghawar, measuring 280 by 30 km, which is by far the largest conventional oil field in the world [14]. Kuwait currently produces approximately 3 MBPD and plans to increase it up to 3.2 MBPD by 2015. In the so-called Partitioned Neutral Zone, shared between Saudi Arabia and Kuwait, Chevron Corp. is involved in an EOR scheme aimed at developing heavier crudes using steam flooding. This technique would likely rely on a system like the BrightSource Energy system Chevron is using in Southern California for the same purpose [15].

In the UAE, the Abu Dhabi Company for Onshore Oil Operations (ADCO) initiated an EOR project in November 2009 to test the injection of CO2 into the North-East Bab Field, a complex carbonate reservoir. Masdar, a subsidiary of Mubadala, is supplying up to 60 tonnes of CO2 per day which is injected into a series of pilot wells. ADCO’s main objectives for utilizing CO2 EOR are to significantly increase reserves, sustain long term production, and maximize ultimate recovery. The UAE is a signatory to the Kyoto Protocol and is therefore committed to reducing greenhouse gas emissions.

2.1.2. Non-OPEC countries:
Oman is currently investing heavily into EOR methods such as Steam Assisted Gravity Drainage (SAGD) techniques as a consequence of falling production from Occidental (since 2001), the operator of the Mukhaizna
field. This initiative resulted in a tenfold rise in daily oil production from 2005 [13]. Today, EOR applications account for a significant portion of Oman’s annual natural gas consumption. By incorporating solar steam from CSP, Petroleum Development Oman (PDO) could significantly reduce the amount of natural gas it burns to produce steam for EOR.

PDO, the largest producer of oil and gas in Oman, and GlassPoint Solar, a U.S.-based renewable energy company in California’s Kern County, installed the Middle East’s first solar enhanced oil recovery (EOR) project. The solar EOR project, which is a 7 MW system, produces a daily average of 50 tons of emissions-free steam that feeds directly into the existing thermal EOR operations of PDO’s Amal West field in Southern Oman [16]. GlassPoint’s solution can cut natural gas used for EOR by up to 80%, helping Oman release its natural gas resources for higher value applications such as power generation, desalination, industrial development or export as LNG [17].

Other countries such as Egypt and Sudan, which also have large reserves of heavy oil, rely extensively on thermal techniques such as Cyclic Steam Soaking (CSS) and SAGD. By 2020, 50% of Sudan’s reserves will be heavy oil, which will mostly need producing through thermal enhanced oil recovery [18].

2.2. Integration of CSP Technologies

There are three major categories of EOR that have been found to be commercially successful to varying degrees:

- **Thermal recovery**, which involves the addition of heat from steam to lower the viscosity, or thin, the heavy viscous oil, and improve its ability to flow through the reservoir.
- **Gas injection**, which uses gases such as natural gas, nitrogen, or carbon dioxide for expanding and pushing additional oil towards the production wellbore or other gases that dissolve in the oil and decrease viscosity to improve flow rates.
- **Chemical injection**, which can involve the use of long-chained molecules (polymers) to increase the effectiveness of water flooding, or the use of detergent-like surfactants to help lower the surface tension that often prevents oil droplets from moving through a reservoir.

Amongst the three types of EOR techniques, it is possible to integrate CSP only for thermal or steam recovery. CSP cannot be used or integrated easily in gas injection and chemical EOR.

**Temperatures Required for Thermal EOR**

Each field requires steam to be injected at a specific temperature for the process. Differences in reservoir depths set the pressure for the steam, and each particular oil field therefore has its own temperature requirements. The temperature levels are usually around 350°C. Superheated steam can be readily achieved using CSP technologies. CSP technologies like parabolic trough (PT), linear Fresnel (LF) and solar tower or central receivers (CR) can provide steam in a wide range of temperatures from 300°C to up to 550°C. Each CSP plant has a steam generator, which produces steam and this steam is fed to the steam turbine to generate power. In case of CSP for EOR, the steam produced can be directly injected in the oil field; depending on the temperature required, the temperature can be adjusted.

**Water Requirement for Producing Steam**

Since most of the CSP plants for EOR will be located in desert or arid regions, the availability of water for producing steam could be problematic. However, EOR applications do not require high purity water – and in fact, EOR applications typically produce heavily polluted water. After treatment, however, it can be re-used, converted back into steam and re-injected into the field. Hence, water is not a major issue for integration of CSP in steam EOR process.

**Constant Supply of Solar Steam?**

Because of seasonal variation of solar energy, a CSP-based steam EOR may not be able to feed steam to the oil field on a constant basis. However, a recent study has proven that for the same cumulative amount of steam injected (during the same period), the oil recovery from solar generated steam injection and that from constant rate steam injection are essentially the same, both for fractured reservoir and for non-fractured reservoirs [19].

Since solar EOR systems can easily be integrated with existing gas-fired steam generation systems, hybrid configurations could be used to supply 24 hours a day steam production, all year long, under varying solar weather conditions. Oilfields in areas lacking natural gas can especially benefit from CSP, creating and injecting steam for EOR purposes without the capital investment of a gas infrastructure. This will particularly appeal to regions where natural gas is unavailable or is in limited supply, such as parts of the Gulf Cooperation Council (GCC) [20].

**Costs**

To produce oil from wells after primary and secondary recovery, more energy and expenses are required than
the equivalent energy and expenses recovered; upon which retirement of the well ensues. EOR methods are extremely costly and the decision to push forward with EOR largely depends on the economic context (petroleum prices). This will in turn dictate if an oil company will decide to freeze production or proceed with EOR. EOR expenses during tertiary exploitation depend on the method used, as well as the heat source. With large uncertainty in global gas prices, EOR using conventional sources is becoming increasingly costlier, which in turn increases the cost of oil recovery.

The major benefit of EOR using CSP lies in the low running costs. Steam represents as much as 60% of the production cost for heavily oil extraction. Solar EOR could supply up to 80% of a field’s annual steam requirements. In addition to being cost competitive with gas, solar EOR provides an edge against long-term gas price escalation. Solar EOR can generate steam at an average cost from $1.75 to $3.00 per MMBTU [21].

Overall costs of CSP technology, more specifically the cost of parabolic trough plants, have been proven to be lower than for conventional steam generation used in thermal EOR today. Although the capital cost of CSP technology may be higher, the overall operating costs are much lower than from conventional fuels, and as a result, CSP could viably provide the necessary heat.

2.3. Case study: US CSP EOR market

Background of US EOR market

The United States have been using EOR for several decades. For over 30 years, oil fields in the Permian Basin have implemented CO₂ EOR using naturally sourced CO₂ from New Mexico and Colorado. The Department of Energy (DOE) has estimated that full use of “next generation” CO₂-EOR in the United States could generate an additional 240 billion barrels (38 km³) of recoverable oil resources. The DOE also estimates that if the EOR potential were to be fully realized, state and local treasuries would gain $280 billion in revenues from future royalties, severance taxes, and state income taxes on oil production, aside from other economic benefits [22].

Thermal EOR techniques account for over 40% of U.S. EOR production, primarily in California. Gas injection accounts for nearly 60% of EOR production in the United States whereas chemical EOR techniques account for only about 1% of U.S. EOR production. In the U.S., there are about 114 active commercial CO₂ injection projects that together inject over 56 million cubic meters of CO₂ and produce over 280,000 MBPD [23].

Potential for CSP based EOR in California:

California is a promising geography for solar EOR with its high level of sunshine and vast heavy oil reserves. Currently, 40% of California’s oil production deploys steam injection for EOR and in a few years will grow to 60%. However, analysts say that solar EOR could replace 20% of the natural gas used for EOR in California.

CSP based EOR project in the USA: Coalinga project in Coalinga, California

One of America’s oldest oil fields, the Coalinga Field began operations in the 1890s. Because the heavy crude oil produced at the field does not flow readily, it is more difficult to extract than lighter grades of crude. Chevron enhances oil production from the Coalinga Field by injecting steam to heat the crude, thereby reducing its viscosity and making it easier to produce. This steam is currently generated by burning natural gas. The solar-to-steam project supplements the gas-fired steam generators and helps determine the commercial viability of using heat from the sun instead of natural gas to generate steam.

In October 2011, Chevron Corp. and BrightSource Energy revealed a 29MW solarto-steam facility at the Coalinga Oil Field in Fresno County, California. The project, which uses solar tower technology, uses over 7,600 mirrors to focus the sun’s energy onto a solar boiler. The steam produced is injected into oil reservoirs to increase oil production. The project is the largest of its kind in the world [24]. The Coalinga solar EOR project spans 100 acres and consists of 3822 mirror systems, or heliostats, each with two 10-foot (3-meter) by 7-foot mirrors mounted on a 6-foot steel pole focusing light on a 327-foot solar tower.

Throughout the course of the day, 3822 mirror systems track the sun and reflect its rays to a receiver positioned on a solar tower. Using heat from the concentrated sunlight, the solar tower system produces steam that is distributed throughout the oil field and then injected underground for enhanced oil recovery. The solar demonstration generates about the same amount of steam as one gas-fired steam generator. BrightSource was contracted to provide the technology, engineering and production and construction services, and Chevron Technology Ventures will manage operations of the project. The facility began construction in 2009 and is now in operation.
We hope that this second part of the guide was useful - providing insight into the potential integration of CSP with EOR and desalination.

At CSP Today Sevilla 2013 this potential will be discussed by experts - not only from the CSP industry, but also from desalination and EOR companies.