CONCENTRATED SOLAR PLANTS


1. Introduction

The Lebanon’s energy sector is the most important contributor to greenhouse gas (GHG) emissions in Lebanon with around 10,979 Gg in 2004 constituting 54.09% of the total emissions (MoE/ URC/ GEF, 2012). Heavy fuel oil and diesel oil are the major source of energy in Lebanon, with a small share of hydropower generation.

Yet, Lebanon’s government has committed itself to achieve 12% of its energy supply from renewable energy resources by the year 2020; a commitment reaffirmed in the 2010 Ministry of Energy and Water (MEW) policy paper.

In the light of this target, Concentrated Solar Power (CSP) provides a possible contribution to the future energy mix and is also capable of contributing significantly to carbon dioxide emission reduction.

This Exchange provides an overview of CSP technology and economics in Lebanon, mostly based on a UNDP-CEDRO publication and some other references mentioned below.
Background

CSP technology uses direct normal irradiation (DNI) to generate power. CSP plants use mirrors to concentrate the incident DNI to raise the temperature of a transfer fluid in the receiver and run turbines to generate electricity.

One of the main advantages of solar thermal power plants over other renewable power technologies, such as large-scale photovoltaic and wind energy converters, is the option of energy storage, since thermal energy storage is economically feasible today. Solar thermal power plants can be equipped with thermal full-load energy storage capacity in the range of one to 24 hours which enables CSP plants to contribute more during evening and morning peak hours. During these demand peaks, electricity prices are usually higher than base-load prices, creating an added value for CSP technologies and energy storage.

CSP Concept

Concentrated Solar Power is a technology which produces electricity by concentrating solar energy in a single focal point. This concentrated energy is then used to heat up a fluid, produce steam and activate turbines that produce electricity. The focusing of solar power can be achieved through different techniques such as parabolic trough, parabolic dish or power tower systems. CSP can also provide combined heat and power, particularly for desalination plants.

The exploitation of solar energy differs substantially depending on sunlight conditions. The desert regions, such as various areas within the Mediterranean region, with frequent sunshine, are ideal places for the deployment of CSP technologies.

Today’s technology of CSP systems is implemented in the cost range of $c13-39 per kWh (based on UNDP-CEDRO publication: Concentrated Solar Power). The wide cost range depends on the technical aspects such as the type and size of the CSP system, the regional aspects such as the available solar resources and the financial aspects such as interest rate, governments incentive, and so forth. The lifetime of CSP technologies is about 20 to 30 years.

CSP cost competitiveness is not only impacted by the cost of the CSP technology itself, but also by the potential rise of fossil fuel prices and by the internalization of external costs, particularly those associated with GHG emissions.

CSP Plant Site Selection

Several criteria are used for CSP plant site selection, of which the most important are;

- Availability of solar resources: DNI larger or equal to 6 kWh/m2/ day
- Availability of accessible and unpopulated land, excluding environmentally sensitive lands and water features.
- Availability of flat land depending on technology
- Availability of water for cooling depending on technology
- Proximity to the electricity grid
- Cost of land leasing
- Potential climate risks
- Political stability of the area
- Existence of government incentive schemes
- Existence of Power Purchase Agreement

CSP Applications

The main application for CSP is electricity generation. However, there are further applications such as:

- Solar gas
- Process heat
- Desalination

Solar Irradiation Map

The figure below shows the potential CSP sites according to solar irradiation levels.

- Blue areas are unsuitable for CSP
• Light yellow areas are suitable for CSP
• Darker yellow areas are good for CSP
• Orange areas are outstanding

Schemes to Implement CSP Plants

Four schemes to implement CSP plants can be distinguished, depending on how to use the resource (solar only or in combination with other fuels; renewable or fossil), and how the collected heat is managed (thermal heat storage and waste heat for co-generation).

Figure 1: Global CSP Potential, Solar Millenium AG

**OPTION 1: Solar-Only**
(Electricity is produced only when DNI is enough)

**OPTION 2: Solar-Only using heat storage**
(Electricity production is partially decoupled from DNI, allowing dispatch ability)

**OPTION 3: Hybrid solar-fuel scheme**
(Electricity dispatch ability is achieved by using solar energy in combination with renewable or fossil fuels)

**OPTION 4: Co-Generation of electricity and heat (for instance to produce desalination)**
(Electricity production is combined with thermal storage, some fuel and a desalination plant)

Figure 2: The Four Implementation Schemes for CSP
Current Global Status

In the last ten years, the industry has expanded rapidly from a newly-introduced technology to become a mass-produced and mainstream energy generation solution.

In many technologies, a log-linear relationship was found between the accumulated experience in CSP, the technical factors and the economic performance.

The rate at which cost declines for each doubling of cumulative production is expressed by the progress ratio (PR). A progress ratio of 90% results in a learning Rate (LR) (4-4) of 10% and similar cost reduction per doubling of cumulative production (Junginger, Sark et al. 2010).

For parabolic trough and solar tower technologies, the learning ratio was found to be of 10%.
CSP In MENA

The Middle-East and North Africa (MENA) region has amongst the world’s best conditions for concentrated solar power (CSP); abundant sunshine, low precipitation, plenty of unused flat land close to road networks and transmission grids.

However, high initial capital costs remain a significant issue for adoption of CSP technology. To make CSP projects in MENA cost-effective in the short to medium term, a combination of factors is necessary, including local incentives, financial schemes, and possible export of green electricity to nearby countries.

MENA, like other emerging regions of the world, has technical and industrial capabilities which are likely to form a good basis on which to build CSP-related activities, as shown for example by the strong auto-parts industry in several countries of the region. It could become home to a new, high potential industry, serving the local markets. The region could benefit from significant job and wealth creation, while the world energy sector would benefit from increased competition and lower costs in CSP equipment manufacturing.

The CSP projects in MENA region as of October 2010 were as follows:

<table>
<thead>
<tr>
<th>Country</th>
<th>Project (Name)</th>
<th>Capacity (MW)</th>
<th>Clean Technology Funds- Financing (US$ million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Algeria</td>
<td>Megahir</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Naama</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hassi R’ mel II</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Egypt</td>
<td>Komo Ombo</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Jordan</td>
<td>Ma’an</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mashereq CSP</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>transmission</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Morocco</td>
<td>Ouarzazate</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>Tunisia</td>
<td>IPP-CSP</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ELMED-CSP</td>
<td>100+</td>
<td></td>
</tr>
<tr>
<td></td>
<td>STEG-CSP</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tunisia-Italy</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td></td>
<td>transmission</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>~1,170</td>
<td>750</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: CSP projects in the MENA CSP IP pipeline as of October 2010

CSP Technologies

The four main CSP technologies are parabolic trough, solar tower, Linear Fresnel collector and parabolic dish. Yet, the majority of existing installations are parabolic trough.

Today, almost all (94%) of installed CSP plants are based on parabolic trough systems, with an overall capacity of around 1.8 GW. Solar Tower plants have an installed capacity of around 70 MW. Plus, there are around 31 MW of Linear Fresnel Reflector systems in Spain and 4 MW in Australia (Photon International, 2009, NREL, 2012 and AEIST, 2012).

1. Parabolic Trough

Long, curved mirrors arranged in a line, concentrate sunlight on pipes located at the mirrors’ focal center. These pipes run down the length of the trough and contain heat transfer fluid which is heated up to as high as 393˚C to produce steam, driving a conventional steam turbine to generate electricity. During the course of the day, a motor rotates the mirrors to track the position of the sun. To limit intermittency and improve dispatch capability, these systems may have molten salt storage or a co-firing natural gas system.
For lower temperature applications, less than 200˚C, the heat transfer fluid is often a mix of demineralized water with ethylene-glycol. For higher temperatures applications, of 200˚C to 500˚C, synthetic oil and molten salts are used.

Parabolic trough power plants consist of large fields of parabolic trough collectors, a heat transfer fluid/steam generation system, a rankine system turbine/generator cycle, and optional thermal storage and/or fossil-fuel back-up systems.

Given sufficient solar inputs, the parabolic trough plants can operate at full-rated power using solar energy alone. During summer months, the plants typically operate for 10-12 hours a day on solar energy at full-rated electric output.

To enable these plants to achieve rated electric output during overcast or night time periods, the plants can be designed as hybrid solar-fossil fuel plants. Thus, a back-up fossil-fired capability can be used to supplement the solar output during periods of low solar radiation.

There are several innovations in parabolic trough technology under development that will undoubtedly have important implications on cost.

Parabolic trough technology is commercially the most advanced of the various CSP technologies, since it offers the lowest cost solar electric option for large power plant applications.

Parabolic trough plants without storage have capital costs as low as 4,600 USD per KW and a capacity factor of 25%. Adding six hours of thermal energy storage increases capital costs to between 7,100 USD and 9,800 USD per kW, but allows capacity factors to be doubled. (IRENA CSP, 2012)

The land use efficiency is of 3.9 ha/MWe. And water requirements are of 800 liters per MWh. (ReGrid CSP, RENAC)

The Levelized Cost of Electricity (LCOE) of parabolic trough plants today is in the range of 0.20 USD to 0.36 USD per kWh. (IRENA CSP, 2012)

Parabolic trough plants with a combined capacity of more than 850MW have been installed to date.

Advantages of Parabolic Trough

- Most commercially viable of the CSP technologies nowadays
- Net plant efficiency of 15% has been commercially proven
- Systems have good land-use factor
- Systems have lower materials demand
- Storage capability
2. Central Receiver Systems

Central Receiver Systems, also known as Solar Towers, use a large array of mirrors, heliostats, to track the sun. The sunlight is reflected from the mirrors onto a central receiver mounted on top of a tower at the center of the heliostat array. Tower technology is now commercial but less mature than trough technologies, but since the solar array focuses the sunlight onto one central receiver, power towers are capable of achieving higher temperatures, high concentration ratios and higher efficiencies. Towers can use various heat transfer fluids, from water and steam to atmospheric or pressurized air, molten nitrate salts and others.

Pressurized gas or air at around 1000 °C can also be used directly to drive efficient gas turbines in modern gas and steam combined cycles.

Molten salt towers raise the potential operating temperature to between 550 and 650°C and offer the potential for very low-cost storage so that solar electricity can meet peak demands and have high capacity factor. Thus, have the potential of making Solar Towers the CSP technology of choice in the future.
Solar Tower plants have a capital cost ranging between 6,300 USD and 10,500 USD per kW for energy storage between 6 and 15 hours. (IRENA CSP, 2012)

Solar Tower technology has a capacity factor ranging from 40 to 80% and a Levelized Cost of Electricity currently from 0.16 to 0.27 USD per kWh. (IRENA CSP, 2012)

**Advantages of Solar Tower**

- Prospects for high efficiencies due to the potential of achieving higher temperatures of over 1000°C
- Can be installed on hilly sites

Gemasolar (connected to the Grid the 1rst of May of 2011)
3. Linear Fresnel Reflectors (LFR)

The approximate shape of parabolic troughs have long curves of flat or slightly curved mirrors which reflect the solar radiation into downward-facing linear, fixed receivers. A more recent design, however, known as Compact Linear Fresnel Reflectors (CLFR), has two parallel receivers for each set of mirrors and thus uses less land than parabolic trough to produce a given amount of electricity. LFR systems heat water running through the receivers directly to generate steam at around 270˚C, thereby, eliminating the need for synthetic heat transfer fluids and heat exchangers.

The main disadvantage of Linear Fresnel Reflectors is that they are less efficient than Parabolic Troughs, having a solar-to-electricity conversion efficiency of 8-10%. (ReGrid CSP, RENAC)

Advantages of Linear Fresnel Reflectors

- Lower manufacturing and installation costs than parabolic troughs
- Less land area required to produce a given amount of electricity

Hybrid operation is possible (in combination with a conventional power coal or gas power plant)

4. Dish

The Dish reflector concentrates the solar radiation into a receiver at the focal point of the dish. The heat transfer medium (fluid or gas) in the receiver is heated at around 750˚C and drives a small piston, stirling engine or micro turbine attached to the receiver to generate electricity directly at the dish. The dish tracks the sun throughout the day. Dish sizes typically range from 5-25 kW. The high solar concentration and operating temperatures have allowed dish systems to achieve solar-to-electricity conversion efficiencies up to 30%.

The main asset of Dish technology is that it doesn’t require water for cooling. However, more research and development are still required for this technology to become mature. No large scale commercial plants have been installed yet, thus, the performance and
costs haven’t been commercially proven. The current energy cost from Dish technology is around twice that of parabolic trough.

**Advantages of Dish**

- High conversion efficiency of around 30%
- No water required for cooling
- Well-suited for remote, stand-alone applications

**Capacity Factor**

The capacity factor of a power plant is the ratio of the actual energy generated in a given period to the energy that could potentially be generated if the plant operated at full output continuously.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Capacity Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parabolic Trough</td>
<td>25-53%</td>
</tr>
<tr>
<td>Solar Tower</td>
<td>40-80%</td>
</tr>
<tr>
<td>Linear Fresnel Reflector</td>
<td>17%</td>
</tr>
<tr>
<td>Dish</td>
<td>50%</td>
</tr>
</tbody>
</table>

**Table 2: Capacity Factor of CSP Technologies, ReGrid CSP, RENAC**

**Water Requirement**

CSP Plants typically require large amounts of water for cooling. The lower the efficiency of the system, the greater the water requirement for cooling because there is more waste heat.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Water Cooling Requirement (Liters/ MWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fossil Fuel Power Plant</td>
<td>800</td>
</tr>
<tr>
<td>Parabolic Trough</td>
<td>3000</td>
</tr>
<tr>
<td>Solar Tower</td>
<td>2000</td>
</tr>
</tbody>
</table>

**Table 3: Water Requirement for Cooling for CSP Technologies, ReGrid CSP, RENAC**

**Technology Comparison**

Each technology has its own value proposition and therefore, different deployment optima, as shown in Figure 5.
Actual Costs

Although Solar Thermal Electricity's (STE) technological improvements present a significant opportunity for improving economies of STE projects, cost evolutions are not solely dependent on technology. Uncertainty of future projects and business instability both lead developers and manufacturers to temporarily inflate their prices in order to manage the risk of their investment. As such, demand currently plays a key role in respect of the cost of electricity from this technology. Government support that fosters the deployment of this technology is of utmost importance for the STE industry.

According to the ESTELA Roadmap study: "a high level overview of the industry vision should lead the electricity cost produced with CSP from actual values of about 17-23 c€/kWh (with solar resource ~ 2000 kWh/m2/year) paid with feed-in tariffs of about 27 c€/kWh in Spain to about 6-10 c€/kWh (with tariffs greater than 10 c€/kWh) by 2025." The roadmap assumes a deployment of about 12 GW for 2015 worldwide and about 60 GW for 2025.
In the longer term, to make concessional finance less critical, generation costs will need to be dramatically lower.

By 2015, when most of the expected CSP technology improvements will be implemented in new plants, energy production boosts greater than 10% and cost decreases up to 20% are expected to be achieved. (UNDP-CEDRO publication)

Economics of CSP for Lebanon

CSP continues to have high investment and production costs. Based on UNDP-CEDRO publication, levelized electricity costs range from $17-25 per kWh, mostly dependent on the quality of the solar resource. For instance, values for Spain, with a similar annual Direct Normal Solar Radiation Resource to Lebanon, are:

- Investments in the order of ~200 M€ for a 50 MWe Parabolic Trough independent (not connected to a conventional one) plant and without heat storage (this produces ~100,000 MWh of electricity per year with Levelized Electricity Cost (LEC) of ~17-19 c€/kWh)

- Investments in the order of ~300 M€ for a 50 MWe Parabolic Trough plant without heat storage (this produces ~180,000 MWh of electricity per year with LEC of ~17-19 c€/kWh)

Techno-Economic Assessment for CSP in Lebanon

The objective of this analysis is to assess the performance and cost of the most mature CSP technologies in a good location in Lebanon and to compare those findings to two other locations: one in South-West USA and one in South of Spain where 95% of CSP plants are being implemented.

The findings are based on UNDP-CEDRO publication written in 2011, thus, the values might be different as the time of this publication.
While the comparison of the levelized cost of electricity is as follows:

![Figure 9: Comparison of LCOE](image)

![Figure 8: Relationship between investment cost, technology type and solar multiple](image)
It is shown that the lowest levelized cost of electricity for Hermel would be in the order of 23 USD cents per kWh of electricity using parabolic trough technology with 7.5 thermal storage, or using Central Receiver technology with 15 hours thermal storage. This cost is cheaper than current (as of 2013) average generation costs of electricity in Lebanon. The recommended schemes for Lebanon would be to use of significant thermal heat storage, due to its lower LCOE and high capacity factors. However, within these schemes, no clear advantage of any of the technological options (parabolic through versus central receiver) may be stated.

CSP Potential for Lebanon

The potential for CSP in Lebanon was estimated taking the following criteria into account:
- Direct Normal Irradiance larger or equal to 2100 kWh/m²/year
- Solid and unpopulated land
- Land slope less or equal to 3%
- Water availability
- Minimum land of 1km²

The CSP technology that was used for the purpose of this assessment was the parabolic trough. Other technologies like solar tower might lead to a different potential considering that this technology can be implemented on hilly sites. The potential areas were found to be as follows:

Figure 10: CSP Potential Map for Lebanon
Table 4: CSP Potential in Lebanon

<table>
<thead>
<tr>
<th>DNI in KWh/ m²</th>
<th>Surface Area in Km²</th>
<th>Capacity in MW</th>
<th>Annual Yield in GWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>2100-2200</td>
<td>18.5</td>
<td>925</td>
<td>1,790</td>
</tr>
<tr>
<td>2200-2300</td>
<td>17.2</td>
<td>860</td>
<td>1,741</td>
</tr>
<tr>
<td>2300-2400</td>
<td>10.9</td>
<td>545</td>
<td>1,153</td>
</tr>
<tr>
<td>2400-2500</td>
<td>8.9</td>
<td>445</td>
<td>981</td>
</tr>
<tr>
<td>2500-2600</td>
<td>30.9</td>
<td>1,545</td>
<td>3,545</td>
</tr>
<tr>
<td>2600-2700</td>
<td>50.8</td>
<td>2,540</td>
<td>6,058</td>
</tr>
<tr>
<td>2700-2800</td>
<td>16</td>
<td>800</td>
<td>1,980</td>
</tr>
<tr>
<td>2800-2833</td>
<td>8.1</td>
<td>405</td>
<td>1,027</td>
</tr>
<tr>
<td>Total</td>
<td>8,065</td>
<td>18,275</td>
<td></td>
</tr>
</tbody>
</table>

Table 4 shows that Lebanon has significant potential for CSP that it can tap into. The assessment was based on 15% annual average solar to electric efficiency and 30% land use factor. If only 15% of the total land area is used, then the potential stands at 1,210 MW of CSP power to be made use of in Lebanon, with a subsequent power supply of 2,741 GWh. If total energy demand stands at 15,000 GWh (2009 estimate), then CSP, with only 15% land usage, can deliver 18.27% of this total demand on aggregate.

Combining CSP with energy storage and/or hybrid natural gas or other, and the achievable objectives and conditions for the future electricity system in Lebanon can be exceptionally improved in terms of ‘greening’ the sector while simultaneously safeguarding reliability. Combining CSP with hydropower and large-wind farms, Lebanon is well suited to be on the frontiers of nations who utilize renewable energy power.

**Conclusion**

Parabolic trough and solar towers are currently the most advanced and commercially proven of the four CSP technologies. The recommended technology scheme for Lebanon would be the use of significant heat storage, making the technology economically viable.

The levelized cost of electricity for a potential CSP plant in Hermel with thermal storage was found to be around $c23/kWh in 2011, yet, the promised technology improvements and the increasing experience in this sector may lead to a cost reduction of approximately 20% by 2015.

With a total potential of 18,275 GWh in Lebanon using parabolic trough technology, CSP promises to be an economically viable solution for the Lebanese electricity problem and a good approach to reduce the country’s high greenhouse gas emissions main
References

• Renewable Energy Technologies: Cost Analysis Series, CSP. Volume 1, Issue 2/5, 2012. IRENA
• ReGrid Concentrated Solar Power 2012- Renewables Academy