CONCENTRATED SOLAR POWER for LEBANON

2012

A Techno-economic Assessment

UNDP

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CONCENTRATED SOLAR POWER (CSP)

for LEBANON

A Techno-economic Assessment

2012

MINISTERIO DE ASUNTOS EXTERIORES Y DE COOPERACIÓN
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°C, Degrees Celsius

€, Euro

AA, Atmospheric Air

Capacity factor, The ratio (usually expressed as a percentage) of the actual electrical generation to the maximum possible generation for a given period of time (usually on an annual basis).

CIEMAT, Spanish Center for Energy, Environment and Technological Research

CR, Central Receiver

CRS, Central Receiver System

CR-CSP, Central Receiver Concentrating Solar Power Plant

CSP, Concentrating Solar Thermal Power. (also Termed Solar Thermal Power, **STP**, and Concentrating Solar Thermal, **CST**): a method of converting sunlight into electricity by means of capturing concentrated solar energy. CSP technology focuses the suns rays by mirrors, flat or curved, onto a collector or receiver to heat or boil a fluid for use in an energy conversion system such as a steam Rankine cycle for generating electricity.

CTF, Clean Technology Fund

Debt/equity ratio, The comparison of the amount of capital assets financed by bank loans requiring interest payments vs. those assets financed by equity capital from investors.

Dispatch ability, The ability of a power supply system to follow load. That is, power can be generated from a plant or collection of plants when it is needed to meet peak system power loads.

DLR, Deutsches Zentrum für Luft-und Raumfart e.V.

DNI, Direct Normal Irradiance is the amount of solar radiation received per unit area by a surface that is always held perpendicular (or normal) to the rays that come in a straight line from the direction of the sun at its current position in the sky. Typically, you can maximize the amount of irradiance annually received by a surface by keeping it normal to incoming radiation. This quantity is of particular interest to concentrating solar thermal installations and installations that track the position of the sun.

DSG, Direct Steam Generation

ESCWA: United Nations Economic and Social Commission for western Asia

EU, European Union

FCR, Fixed Charge Rate, The annual interest expenses of the money borrowed to build a new construction project, plus the annual costs to operate and maintain it. Fixed charge rates include a range of factors such as construction financing, financing fees, return on debt and equity, depreciation, income tax, property tax, and insurance. The fixed charge rate, when multiplied by the cost of a new construction project, yields the annual “fixed charges.”

FIT, Feed-in- Tariff, A feed-in tariff (FIT, standard offer contract advanced renewable tariff or renewable energy payments) is a policy mechanism designed to accelerate investment in renewable energy technologies. It achieves this by offering long-term contracts to renewable energy producers, typically based on the cost of generation of each different technology. Technologies like wind power, for instance, are awarded a lower per-kWh price, while technologies like CSP and tidal power are currently offered a higher price, reflecting their higher costs. (In Spain CSP: 26.94 eurocents/kWh for 25 years, increasing annually with inflation minus 1%, plant size limit 50 MW; after 25 years 21.5 eurocents/kWh; the FIT is limited to 500 MW of new installations per year. Note: Economically optimum CSP plant sizes range from about 100-250 MW. For comparison: In France the CSP FIT is 30 eurocents/kWh since 2006, and in Italy 22-26 eurocents/kWh since 2008.). In addition, feed-in tariffs often include "tariff degression", a mechanism according to which the price (or tariff) ratchets down over time. This is done in order to track and encourage technological cost reductions. The goal of feed-in tariffs is ultimately to offer cost-based compensation to renewable energy producers, providing the price certainty and long-term contracts that help finance renewable energy investments.

GW_e, Gig watts electric. A measure of electric power generation. One GW_e equals one billion (10^9) watts or 1 million kilowatts.

GWh, Gigawatt-hours

h, Hours

HTF, High Temperature Fluid

IEA, International Energy Agency

Kg, Kilograms

km^2, Square kilometre

kW, Kilowatts

$kW_{e,l}$, Kilowatts-electrical

$kW_{th,}$, Kilowatts-thermal

Levelised electricity cost (LEC), The Levelised cost of energy (LCOE) (or Levelised electricity cost, LEC) is the most common basis used for comparing the cost of power from competing technologies. The levelized cost of energy is found from the present value of the total cost of building and operating a generating plant over its expected economic life. Costs are levelized in real euros or dollars, i.e., adjusted to remove the impact of inflation.

m, Meter

m^2, square meter

m^3, cubic meter

MENA, Middle East and North Africa Region

MENA CSP IP, MENA CSP Scale-up Investment Plan

MS, Molten Salt

MW, Megawatts

MW_e, Megawatts electric. A measure of electric power generation. One MW_e equals 1 million watts or 1,000 kilowatts.

$MW_{el,}$, Megawatts-electrical

MWh, Megawatt-hours

$MW_{th,}$, Megawatts-thermal

O&M, Operating and Maintenance

PSA, Plataforma Solar de Almería (Resear Division of CIEMAT Center in Almería, Spain)

PV – Photovoltaic. A means of generating electricity directly from sunlight through solar cells containing materials that are stimulated by the solar energy to produce a flow of electrons.

PT, Parabolic Trough

PTC, Parabolic Trough Collector

PT-CSP, Parabolic Trough Concentrating Solar Power Plant

R&D, Research and Development

Rankine Cycle, A power plant consisting of a closed series of four processes: (1) liquid pressurization, (2) heating-evaporation, (3) vapor-expansion, and (4) cooling-condensation. There are many variations on the basic Rankine cycle in practice.

RES, Renewable Energy Source

s, Seconds

SEGS, Solar Electric Generating Station (Denomination of the first Commercial CSP plants developed in California between 1986 and 1991)

SM, Solar Multiple

Solar PACES, Solar Power and Chemical Energy Systems. Task under the IEA Programme

Supercritical fluid, A fluid that exists at conditions of pressure and temperature in excess of its critical temperature and pressure (its critical point), above which it cannot exist as a liquid but only as a dense fluid.

T, Tons

TES, Thermal Energy Storage

THS, Thermal Heat Storage

Thermal efficiency, For a cycle, the ratio of the net power output to the rate of heat input to the cycle.

TSA, Technology Program Solar Air Receiver

1. Introduction

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 (MoEW) Policy Paper; "This policy commits to launching, supporting and reinforcing all public, private and individual initiatives to adopt the utilization of renewable energies to reach 12% of electric and thermal supply". The share or contribution of electricity or thermal power to this electricity mix was not specified, and therefore left to market and government conditions and policies. However, given the importance of relying on alternative sources of electricity for greenhouse gas (GHG) abatement and enhanced security of supply, and given Lebanon's current electricity deficit and reliance on expensive fuel oil, introducing and increasing the share of renewable electricity is a necessity.

CEDRO ("Country Energy efficiency and renewable energy Demonstration project for the Recovery of Lebanon") has been established with an aim to complement the national power sector reform strategy" and to support the greening of Lebanon's recovery reconstruction and reform activities. The CEDRO 3 project builds on the objectives of the Ministry of Finance and the Ministry of Energy and Water to develop, promote and adopt a sustainable energy strategy.

Following CEDRO's work on resource assessment studies with respect to large-wind power applications (wind atlas), and bioenergy potential for Lebanon, this study offers a concise overview of the techno-economic performance of various concentrated solar power (CSP) technologies.

1.1. Motivation

Concentrating Solar Thermal Power (CSP) can provide critical solutions to global energy problems within a relatively short time frame and is capable of contributing substantially to carbon dioxide reduction efforts. Of all the renewable technologies available for large-scale power production today and for the next few decades, CSP is one of a few alternative technologies with the potential to make major contributions of clean energy because of its relatively conventional technology and ease of scale-up.

Solar Thermal Power is now rapidly advancing in several parts of the world as potentially capable to become a novel, main **primary form of energy**, because of its' **lowering cost** and the **ability of ensuring effective energy storage** to smooth out the time variations of sunlight. Although CSP is only one part of the energy solution, it potentially offers a major supply option in some of the world's largest economies and load centres.

Although innovative energies may be essential to developing countries, technically developed countries (e.g., Spain, Germany and United States of America) are providing the required technological maturity to foster such a change.

The actual deployment of CSP is already significant (with about 220 projects amounting 10 GWe with different degree of development; 1.4 GWe already connected to electrical networks, about 3 GWe under construction and about 5.5 GWe under project development), and deployment rates are growing so that cost figures and the technological risk perception must be updated continuously.

Today's technology of CSP systems is implemented in the cost range of **10 -30 €cents/kWh**, with a wide cost range (Figure 1) which depends on: i) technical aspects as the type and size of CSP technology chosen; ii) regional aspects, as the "typical" solar resource (direct normal irradiation, DNI) on the site, the local cost for installation, the operation and maintenance costs, etc… and; iii) financing aspects, as interest rate, government incentives, etc.

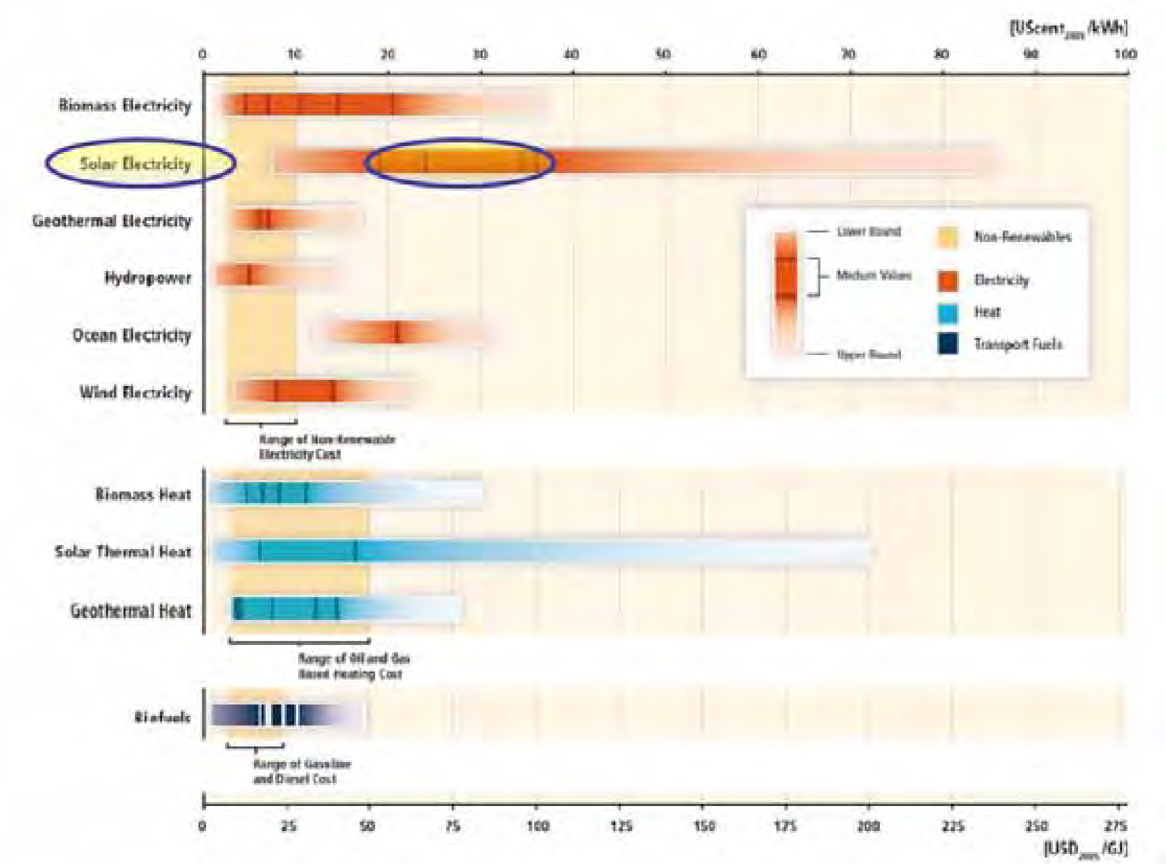


Figure 1. Comparative energy costs for different sources (IPCC, 2011).

It may be observed how in several scenarios solar electricity is already competitive with conventional electricity (Source: Intergovernmental Panel on Climate Change IPCC-XXXIII/Doc. 20(9.V.2011))

Cost competitiveness is not only impacted by the cost of the technology itself but also by a potential rise of the price of fossil energy and by the internalization of external cost, particularly those associated with CO_{2e}-emissions. Thus, for instance, a recent report from World Watch Institute on the “Nuclear Energy Status after Fukushima” accident shows that the implementation of additional security standards in the Nuclear power plants lead the cost of the electricity to overpass the cost of solar Photovoltaic electricity in 2010 (Figure 2).

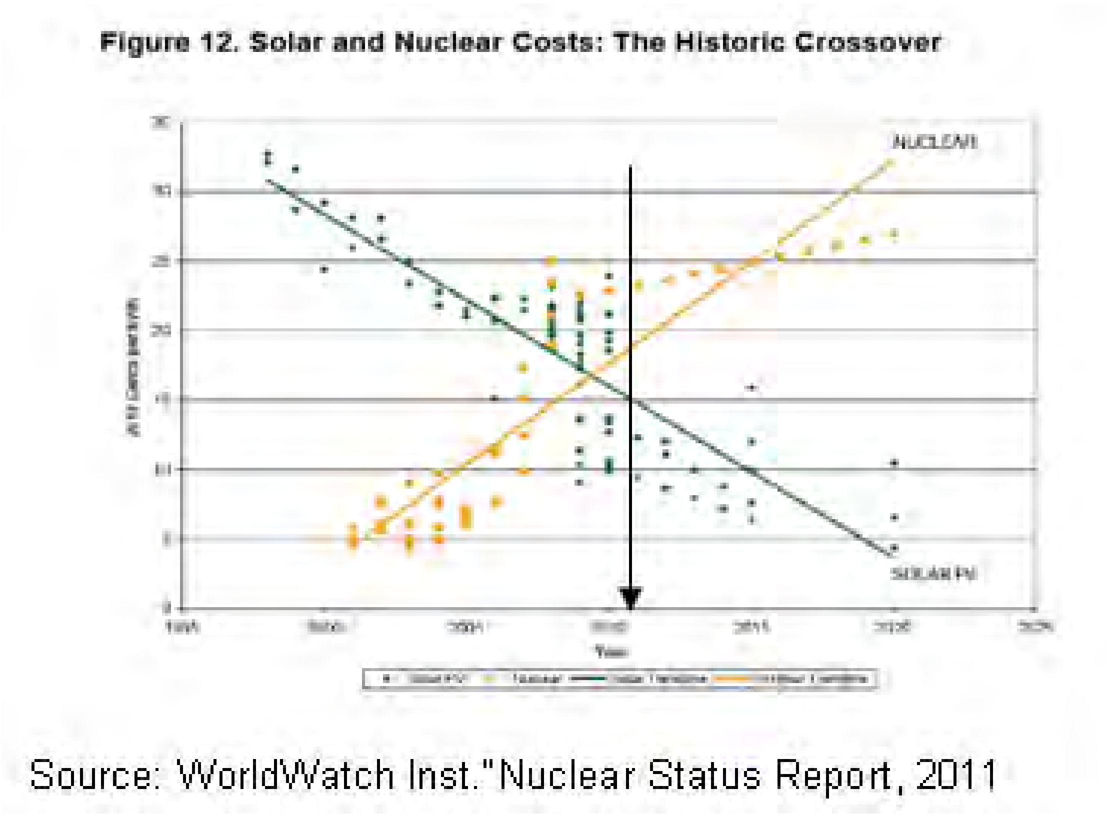


Figure 2. Solar and nuclear Costs. The historic Crossover

Given that CSP technology components are produced from readily available commodities such as steel and glass, bottlenecks to CSP market growth are not more problematic than other energy options.

In this report we will update the feasibility assessment of CSP technologies for Lebanon by surveying the available commercial options and carrying out an analysis to estimate the performance and electricity costs in a chosen placement in Lebanon in comparison with other regions in which CSP is being promoted, particularly the south of Spain and the south-west regions of the U.S.).

1.2. Report objectives

Among other considerations, this assessment report follows the first "Recommendation" included in the ESCWA (UN) report ("*Possibility and Prospects of Generating Electricity from Renewable Energy Sources in the ESCWA Region*"; Volume 2: Concentrated Solar Power, UNDP, 2001), which is:

"… to expand the current study at the national level of the countries and define the appropriate sites in each country for implementing solar thermal power systems with conducting preliminary studies necessary for this purpose".

Regarding the specific study for Lebanon on the Concentrated Solar Power potential the analysis carried out in the late 90's, the mentioned ESCWA report concludes that:

"Lebanon has negligible potential in CSP due to the land, water, and cloud cover requirements for CSP"

Within the institutional framework of solar energy promotion actions in the country, CEDRO wishes to re-assess the CSP potential given the technological progress achieved in this field during the last decade.

Additional reports and information sources (see references) have also been consulted with special attention to similar studies or roadmaps helping to assess the CSP potential in Lebanon, and with the aim to provide some answers to the driving questions:

1. What has changed in the CSP technology during last decade?
2. Which new driving forces may we identify to foster the viability of CSP in Lebanon?
3. Are CSP technologies sufficiently mature for Lebanon?
4. Which regions would be the most appropriate for CSP deployment within Lebanon?
5. What is the technical/economical potential for CSP in Lebanon?

1.3. What has changed in the CSP technology during last decade?

Technology has changed but most of the technology concepts were already present in the 2000's. In fact most of the designs of the CSP plants were stated as detailed engineering projects in the 2000's. Only some innovations appeared in some components and installation procedures to improve the efficiency/cost ratios.

The significant change has been the acceleration of the technology implementation (with more than a 1.2 GW of power installed in 2010 and about 3 GW under construction). These projects imply a reduction in the technological risk perception. The growing experience in CSP plants operation is leadings to a similar growth of confidence in the technology.

Between 1985 and 1991, the Solar Energy Generating Systems (SEGS), I to IX (parabolic trough) with a total capacity of 354 MW, were built in the Mohave Desert, USA. After more than 15 years, the first new major capacities of Concentrated Solar Thermal Electricity Plants came online with Nevada One (64 MW, USA) and the PS 10 plant (11 MW, Spain) in the first half of 2007. PS 10 includes 0.5 hour of water/steam buffer storage. A somewhat larger tower plant, PS 20 with 20 MW followed in 2009. In 2008, Andasol 1 (with 7.5 hours of storage) and the Ibersol Puertollano plant of 50 MW, each started their operational test phase and became fully operational in 2009. Andasol 2 with another 50 MW started its test operation mid-2009. Since then the deployment has been accelerated so that:

"Worldwide there was 1.2 GW under construction as of April 2009 and another 13.9 GW announced globally through 2014. Spain was the epicenter of solar thermal power development in 2010 with 22 projects of 1,037 MW constructed, one 450 MW already have provisional registration and, in addition, projects with more than 10 GW have filed grid access applications. In the United States, more than 4 500 MW of CSP are currently under power purchase agreement contracts. The different contracts specify when the projects have to start delivering electricity between 2010 and 2014. In developing countries, three World Bank projects for integrated solar thermal/combined-cycle gas-turbine power plants in Egypt, Mexico, and Morocco have been approved. Other countries of the MENA (Middle East and North of Africa) and Asian countries such as Iran and Abu Dhabi have CSP projects under construction or announced.

CSP technologies are currently stepping out of the demonstration phases and entering commercial deployment for power production in Europe. Due to past developments in the USA (~350 MW in operation since 1980), the most mature large scale technology is the parabolic trough/heat transfer medium system. Central receiving systems (solar tower) are the second main family of CSP technology. Parabolic Dish engines or turbines, e.g. using a Stirling or a small gas turbine, are modular systems of relatively small size and are primarily designed for decentralised power supply. The lifetime of CSP technologies is about 20 to 30 years (Stoddard *et al.,* 2006). The solar-only capacity factor without thermal storage of a CSP plant is about 1,800 to 3,000 hours per year (or approximately 20-35%). The level of dispatching from CSP technologies can be augmented with thermal storage or with hybridised or combined cycle schemes with natural gas. With storage, yearly operation could theoretically be increased to 8,760 hours, but this is not economically or technically possible, capacity factors of conventional power plants never reach 100%. Systems with thermal storage generally achieve capacity factors between 3,000 to 6,500 hours (Stoddard *et al.,* 2006). An experimental facility with 19 MW capacity and molten salt storage which should allow almost 6,500 operation hours per year is currently being built by Gemasolar in Spain (Web: Torresol). Several Integrated Solar Combined Cycle projects using solar and natural gas are under development, for instance, in Algeria, Egypt, India, Italy and Morocco (Kautto *et al.,* 2009).

Thus, 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.

The learning curve is quite evident and seems to follow the expected ratio so that the electricity cost might be divided by two after a total power implementation of about 10-15 GWe., which is expected to be achieved by 2017.

In the USA, scaling activity in the south-west along with multiple project commissions adding up to further 7,000 MW are under planning and development which could all come online by 2017.

Countries in bold are home to operational CSP sites. The remaining countries are at various stages of the CSP planning and development process.

Figure 3. Countries with CSP operational

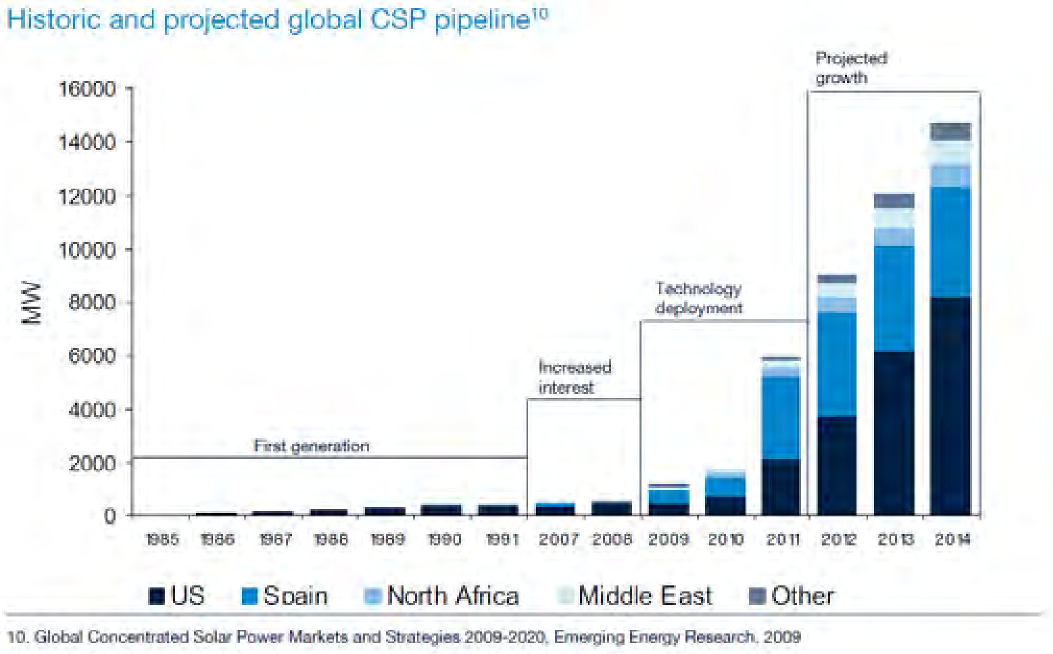


Figure 4. Historic and projected CSP pipeline (Ernst & Young & Fraunhofer and WorldBank, 2011)

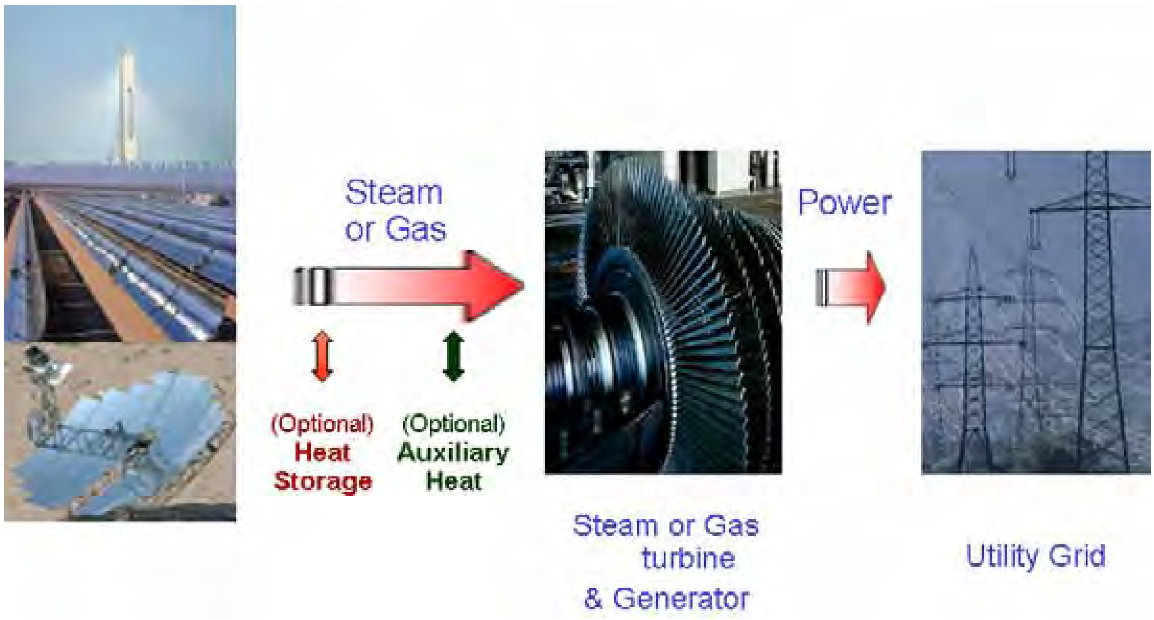
The Middle East and North Africa (MENA) region has amongst the world's best conditions for concentrated solar power (CSP); abundant sunshine, low precipitation, plenty of unused flat land close to road networks and transmission grids. It is also close to Europe, where green electricity is much valued. However, high initial capital costs remain a significant issue for adoption of CSP technology. To make CSP projects in the MENA cost effective in the short to medium term, a combination of factors is necessary, including local incentives, concessional finance and export of green electricity to Europe. The MENA CSP scale-up Investment Plan (MENA CSP IP), supported by the World Bank and the African Development Bank (AfDB), is intended to strategically utilize concessional financing from the Clean Technology Fund (CTF) to accelerate global adoption of the technology in the region. It was endorsed by the CTF Trust Fund Committee on December 2, 2009, and will support expansion programs in five countries of the MENA region, Algeria, Egypt, Jordan, Morocco and Tunisia.

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

Country	Project (Name)	Capacity (MW)	CTF financing (US$ million)
Algeria	Megahir	80	
	Naama	70	
	Hassi R' mel II	70	
Egypt	Komo Ombo	100	
Jordan	Ma'an	100	
	Mashereq CSP transmission	-	
Morocco	Ouarzazate	500	
Tunisia	IPP-CSP	100	
	ELMED-CSP	100+	
	STEG-CSP	50	
	Tunisia-Italy transmission	-	
Total		~1,170	750

1.4. Outline of CSP technologies

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



The hot fluid is then used to generate steam and power a steam turbine. Through the implementation of thermal storage or fossil fuels fired backup, CSP plants can generate electricity according to the demand and thus replace the conventional power plants.

The option of thermal energy storage

One main advantage 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. Unlike the storage of electric energy, **thermal energy storage** is practically and economically feasible today, even in large-scale applications. Solar thermal power plants can be equipped with thermal energy storage with a full-load storage capacity **in the range of one to 24 hours** which enables CSP plants to contribute more power during dawn and dusk periods. Usually, the storage is filled during the day, and emptied again after sunset, so that electricity continues being produced. This allows for plant operation in concordance with load requirements from the grid, especially that peak demand for electricity in most countries are in the late evening hours. During such demand peaks, electricity prices are usually far higher than base-load prices, creating a very important added value of CSP and storage.

Various thermal storage technologies are in principle feasible for solar thermal power plants, based on different physical mechanisms (such as sensible heat storage, latent heat storage, and chemical energy storage), and by applying different types of storage materials (such as molten salt, oil, sand, and concrete). The storage material needs to

be cheap, given that large quantities are required. A comprehensive overview of storage principles and technologies suitable for solar thermal power plants is given in Gil (2010) and in Medrano (2010). It should also be noted that different heat transfer fluids (HTFs) used in the solar field require and allow different storage options.

We may distinguish four **schemes to implement CSP plants**, depending on how we use the resource (solar only or in combination with other fuels renewable or fosil) and how it is managed the collected heat (using or not thermal heat storage and using the waste heat for co-generation):

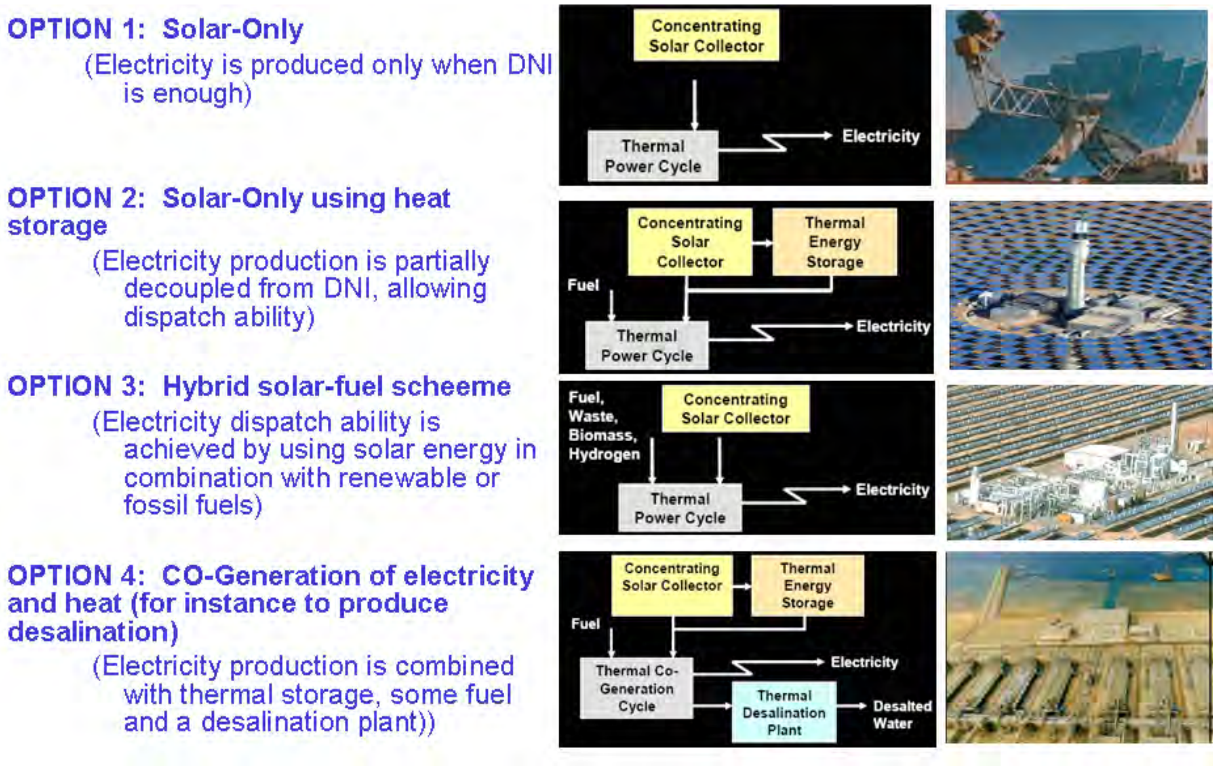


Figure 5. Types of implementation schemes for CSP

Almost all the CSP commercial plants in operation or in development are powering a Rankine cycle (Figure 6) or Integrated the solar heat in a Combined Cycle, ISCC (Figure 7).

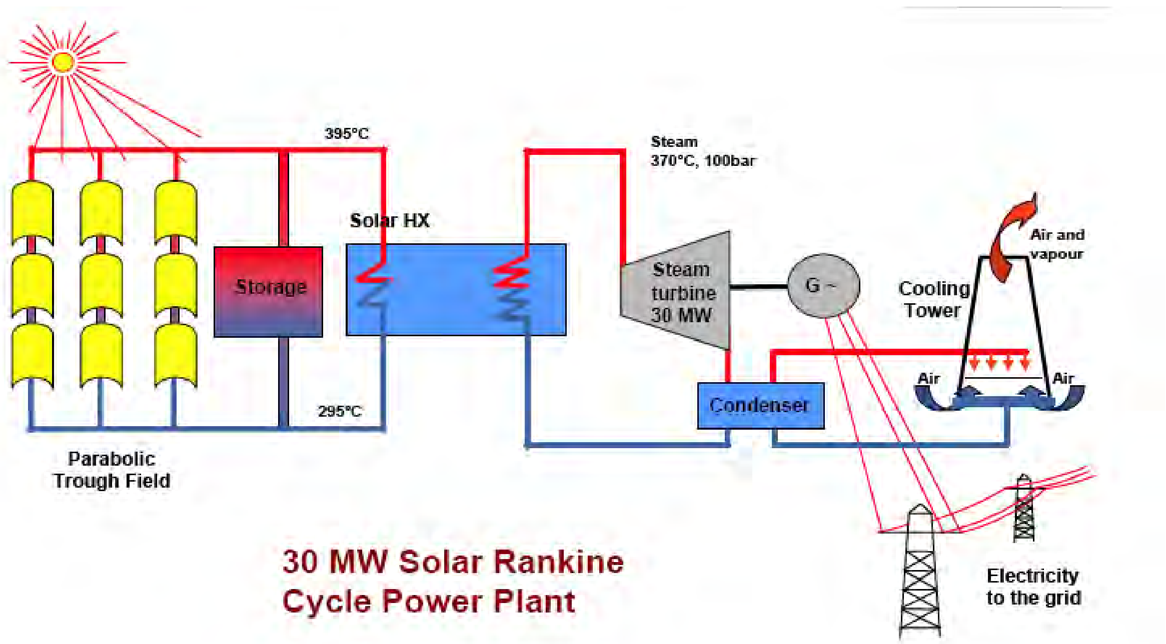


Figure 6. Example of Implementation of CSP in conventional Rankine Cycle

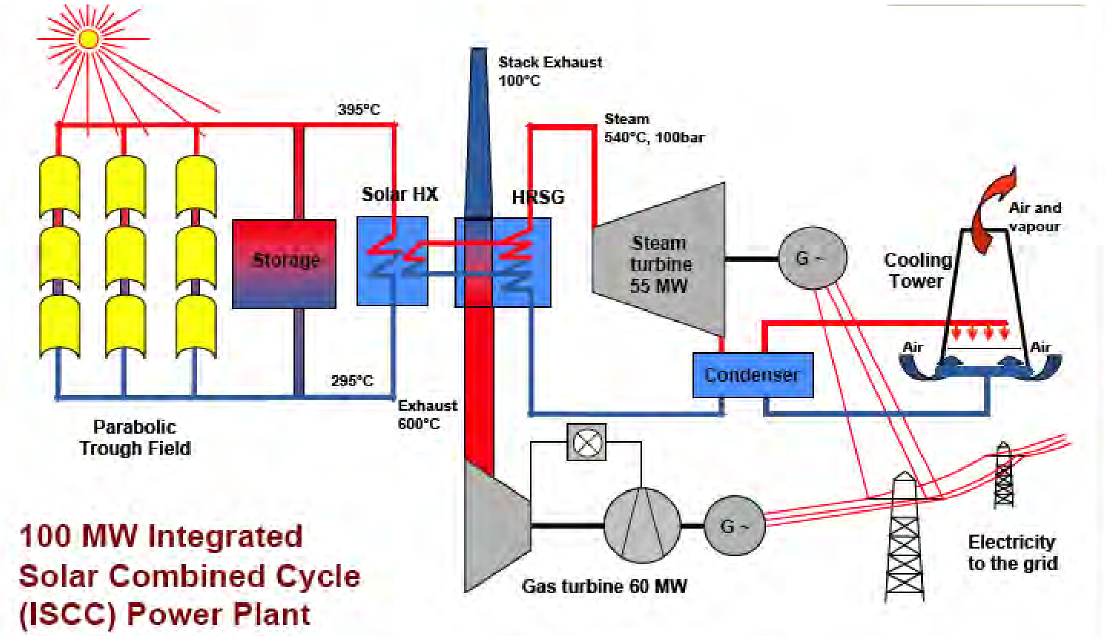


Figure 7. Example scheme of integration of concentrating solar heat into a Combined Cycle.

The ISCC integrates the outlet heat from a solar field into the **combined cycle** which is an assembly of a Brayton type and a Rankine type heat engines that work in tandem. The principle is that the exhaust of the Brayton cycle heat engine is mixed with the heat coming from the solar field as the heat source for the Rankine cycle, thus extracting more useful energy from the heat, increasing the system's overall efficiency.

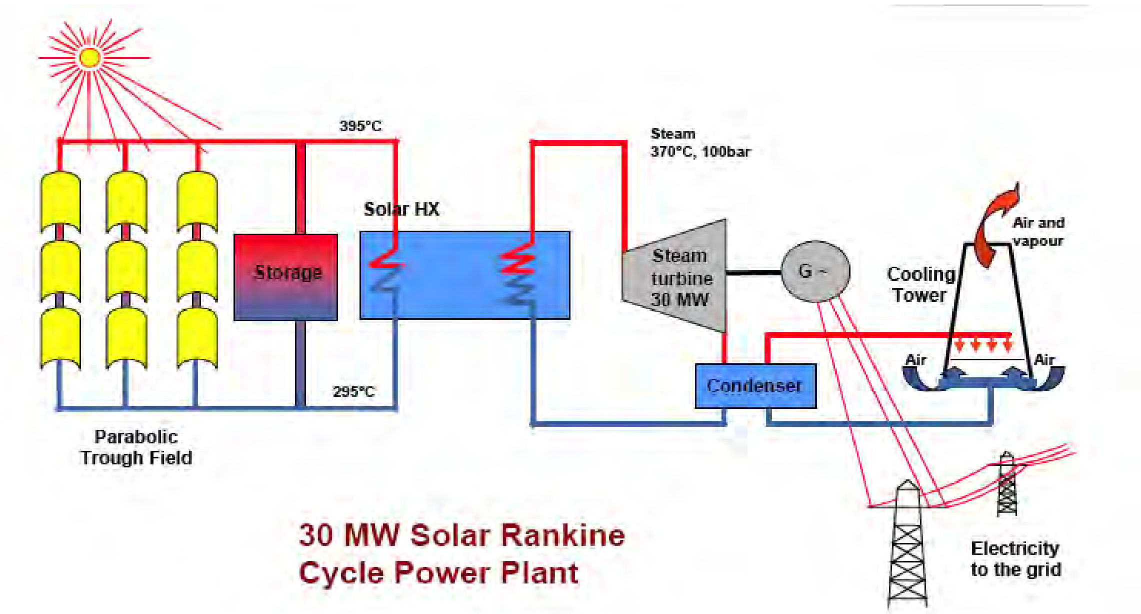


Figure 8. Example scheme of integration of concentrating solar heat into a Combined Cycle (ISCC)

Unlike photovoltaic cells or flat plate solar thermal collectors, CSP power plants cannot use the diffuse part of solar irradiation which results from scattering of the direct sunlight by clouds, particles, or molecules in the air, because it cannot be concentrated.

Concentrating solar collectors are usually subdivided into two types, with respect to the concentration principle:

- Line-focusing systems, such as the parabolic trough collector (PTC) and linear Fresnel collector. These systems track the sun position in one dimension (one-axis-tracking),
- Point-focusing systems, such as solar towers or solar dishes. These systems realize higher concentration ratios than line-focusing systems. Their mirrors track the sun position in two dimensions (two axis-tracking),

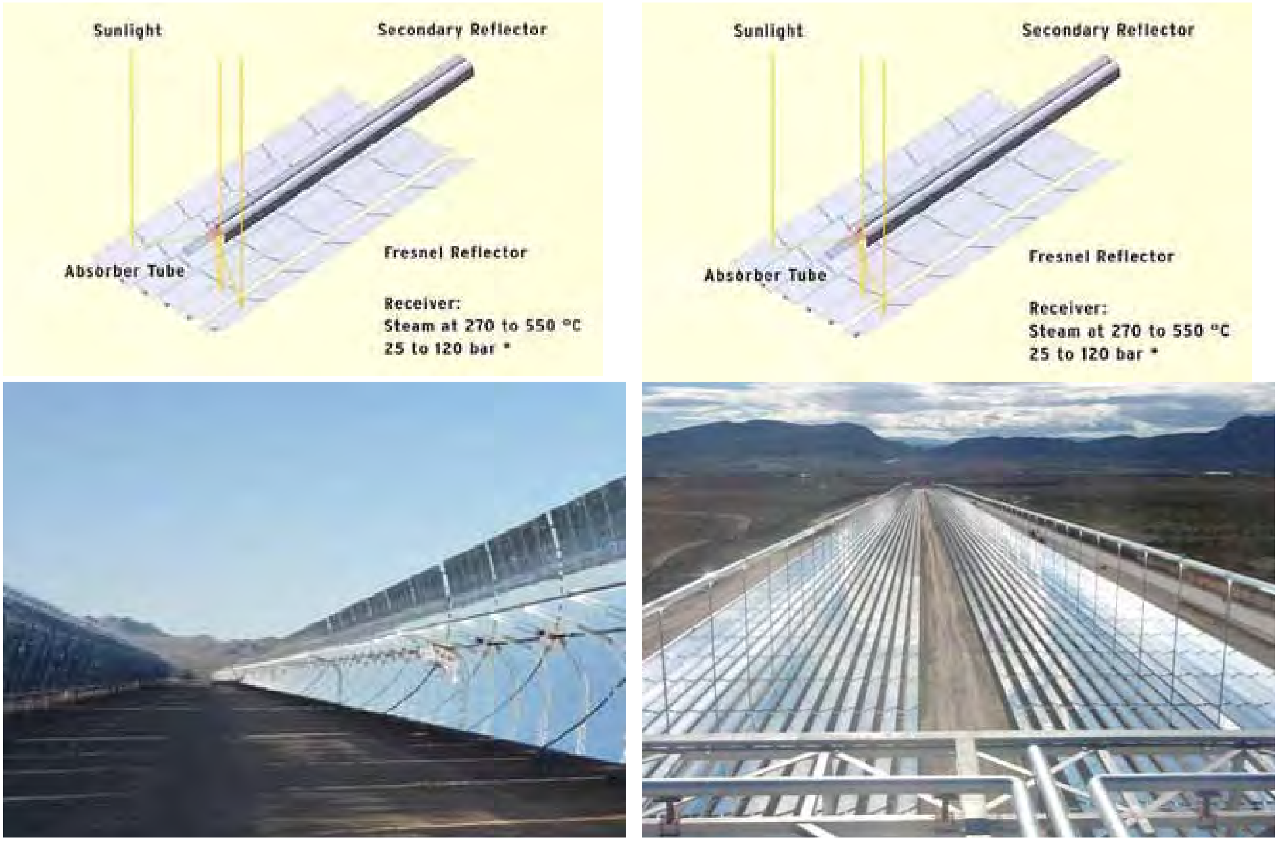


Figure 9. Line-focusing systems: Left: Parabolic trough collector: 64 MW_{el} power plant *Nevada Solar One*; dimensions: collector aperture width 5 m (Morin, 2010). Right: Linear Fresnel Collector: 1.4 MW_{el} plant *PE1* in Murcia, Spain; dimensions: Receiver height above mirror field: 7 m (Novatec, 2010).

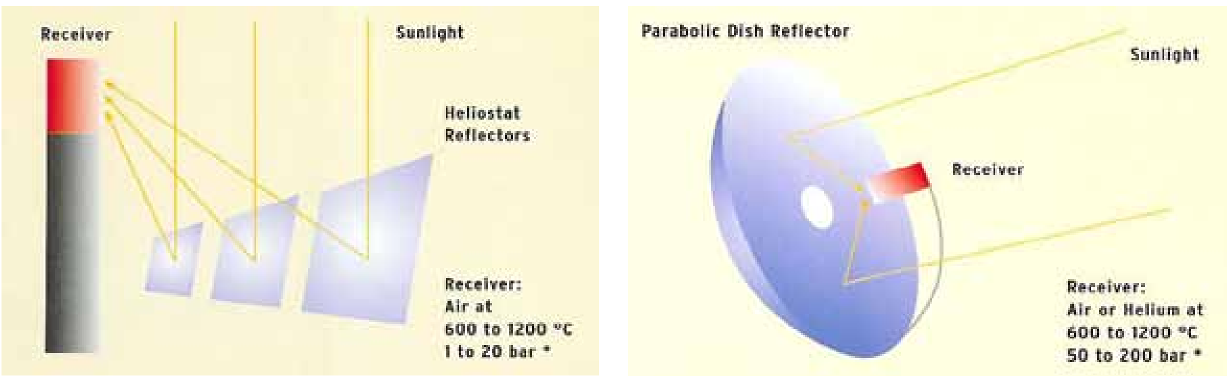


Figure 10. Point-focusing systems: Left: Solar Tower plant PS10, 11 MWel in Seville, Spain; 624 so-called heliostats, 120 m2 each, focus the sunlight onto a receiver on top of a 100 m high tower (Abengoa, 2010). Right: Dish Stirling prototype plants of 10 kWel each in Almería, Spain; diameter 8.5m (PSA, 2010)

Among the line-focusing, **parabolic trough** plants have become commercially bankable, the highest share of announced new projects worldwide (up to 9,000 MW) uses this technology.

Within point-focusing, **central receiver** is the technology more mature with 50 MWe already in operation (all in Spain) but about 1 GWe under construction (mainly in U.S.A.) .

Dish systems: The dish is an ideal optical reflector and therefore suitable for applications requiring high temperatures. Dish reflectors are parabaloid-shaped and concentrate the sun onto a receiver mounted at the focal point, with the receiver moving with the dish. Dishes have been used to power Stirling engines at 600ºC-900°C, as well as generate steam. Operational experience with dish/ Stirling engine systems exist and commercial roll-out is planned. Up to now, the capacity of each Stirling engine is of the order of 3 to 25 kWe. The largest solar dishes have a 400 m2 aperture and are used in research facilities. The Australian National University is presently building a solar dish with a 485 m2 aperture. Dish engines still have some cost disadvantages, but US developers hope to overcome this by mass production and thousands of single installations in a large area (total capacity 800-1,000 MW).

The attraction of **linear Fresnel** reflectors is that installed costs, on a m2 basis, can be lower than troughs, and the receiver is fixed. However, the annual optical performance is lower than for a trough reflector. Although Fresnel technology has the same solar field design, but its mirrors have lower production costs, this technology still lags in volumes of announced projects (the first 30 MW plant in the south of Spain will create commercial experience).

Table 2. Commercial deployment of CSP by technologies (status in 2010) (Source: Sun & Wind Energy 2010).

[MW]	Operational	Under construction	Planning phase[4]	Total
Tower	44	17	1603	1664
Parabolic	778	1400	8144	10322
Fresnel	9	30	134	173
Dish $ Stirling	2	1	2247	2250
Total	833	1448	12128	14409

Availability of water is an issue which has to be addressed for CSP development, as the parabolic trough systems and central tower systems require cooling water. Wet cooling requires about 3 to 5 m3/MWh, which is comparable to other thermal power stations. Air cooling and wet/dry hybrid cooling systems offer highly viable alternatives to wet cooling and can eliminate up to 90% of the water usage. The penalty in electricity costs for steam generating CSP plants range between 2 and 10% depending on the actual geographical location, electricity pricing and effective water costs. The loss of a steam plant with state-of-the-art dry cooled condenser can be as high as 25% on very hot summer days in the US Southwest. The penalty for linear Fresnel designs has not yet been analyzed, but it is expected to be somewhat higher than for troughs because of the lower operating temperature. On the other hand, power towers should have a lower cost penalty because of their higher operating temperature.

The assessment of CSP for Lebanon of **this report focuses mostly on the Parabolic Trough and in Central Receiver** since they are **the most mature** and provides (at present) the lower electricity costs.

1.4.1. Parabolic Trough Collectors (PTC)

Parabolic trough technology is commercially the most advanced of the various CSP technologies. **Parabolic Trough** concentrators use a reflective surface such as a glass mirror to reflect and focus sunlight onto a heat collection tube that runs the length of the mirrors and carries the heat transfer fluid to a turbine generator. To maintain appropriate positioning with the sun’s rays, parabolic troughs “track” the sun, pivoting on a one-axis system. Troughs must be engineered to withstand bad weather, particularly wind.

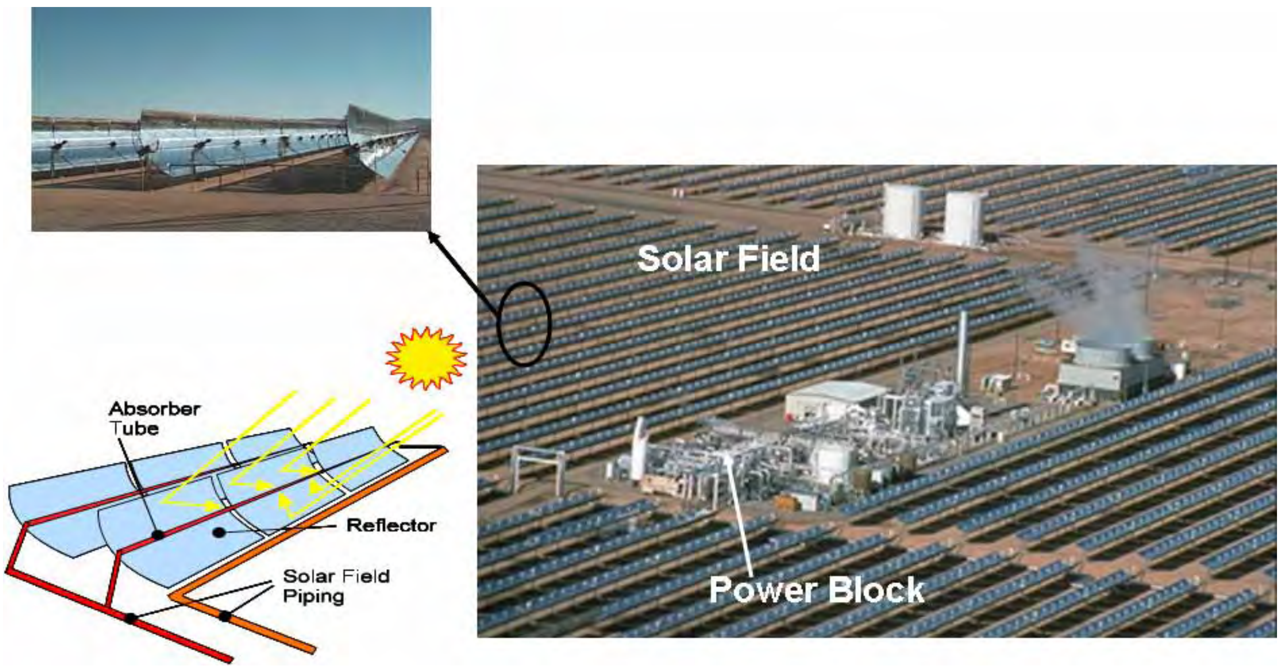
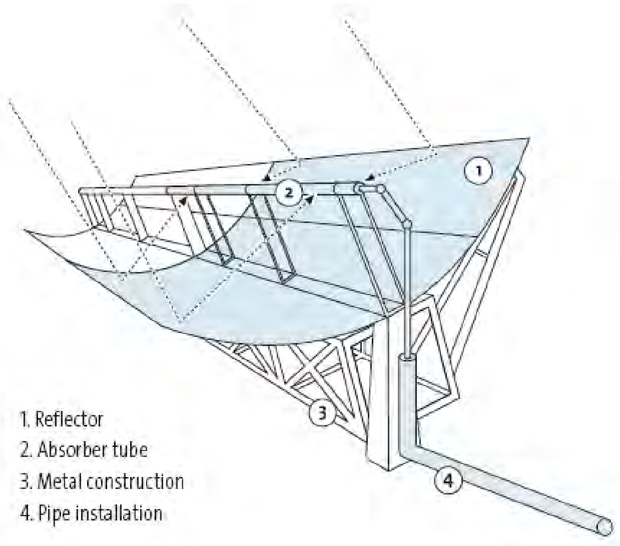


Figure 11. Basic Components of Parabolic Trough CSP (PT-CSP)

Parabolic trough power plants consist of large fields of parabolic trough collectors, a heat transfer fluid/ steam generation system, a Rankine steam turbine/generator cycle, and optional thermal storage and/or fossil-fired backup systems (Figure 6). The collector field is made up of a large field of single-axis-tracking parabolic trough solar collectors. The collectors track the sun from east to west during the day to ensure that the sun is continuously focused on the linear receiver. Each parabolic trough collector (PTC) consists of a receiver, mirrors, a metal support structure, pylons, and foundations. The parabolic-shaped and facetted mirrors concentrate the sunlight onto the receiver tube.

The parabolic shape is usually implemented by four mirror facets, consisting of glass sheets (4 mm thick) which are thermally bent and coated with a reflective silver layer, and with additional protective layers on the back side of the silver. The absorber inside the receiver is realized in the form of a coated steel tube. The coating is spectrally selective in the sense that it absorbs the solar (short wave) irradiation well and emits almost no infrared (long wave) radiation, which reduces heat loss. The absorber tube is surrounded by an evacuated glass tube which is highly transmissive for the sun light due to an anti-reflective coating. The absorber tube and the encasing glass tube together are called the receiver. In today‘s commercial trough systems the entire collector—including the receiver—is tracked according to the moving sun position. Within the receiver, a heat transfer fluid (HTF) is heated up as high as 393ºC as it circulates through the receiver and returns to a steam generator of a conventional steam cycle power plant.



Given sufficient solar input, the plants can operate at full-rated power using solar energy alone. During summer months, the plants typically operate for 1012 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 have been designed as hybrid solar/fossil plants; that is, a backup fossil-fired capability can be used to supplement the solar output during periods of low solar radiation. In addition, thermal storage can be integrated into the plant design to allow solar energy to be stored and dispatched when power is required.

There are several innovations in PTC technology under development or in prototype status. The current developments focus on cost reductions in the assembly and production process (e.g., automized production), lighter collector structures, new materials for collector structures (such as aluminium), and new heat-transfer fluids (e.g., molten salt and direct steam).

LS-3

Solargenix

Figure 12. New designs of supporting structures to reduce the installation cost

1.4.2. Some Commercial Parabolic Trough Collector CSP plants under operation

Figure 13. Andasol 1 and 2 (in Gaudix, Granada, Spain)

Figure 14. Solnova 1,2 and 4 (with PS10 and PS20 above) (in Sanlucar La Mayor, Seville, Spain)

Figure 15. Extresol 1. (Extremadura, Spain)

Figure 16. CTS Puertollano (Puertollano, Ciudad Real, Spain).

Figure 17. La Florida, Alvarado, Spain.

1.4.3. Central Receiver (or Power Tower) CSP

Power 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, higher concentration ratios and higher efficiencies than PTC technologies. Towers can use various heat transfer fluids, from water and steam to atmospheric or pressurized air, molten nitrate salts, and others (Figure 18).

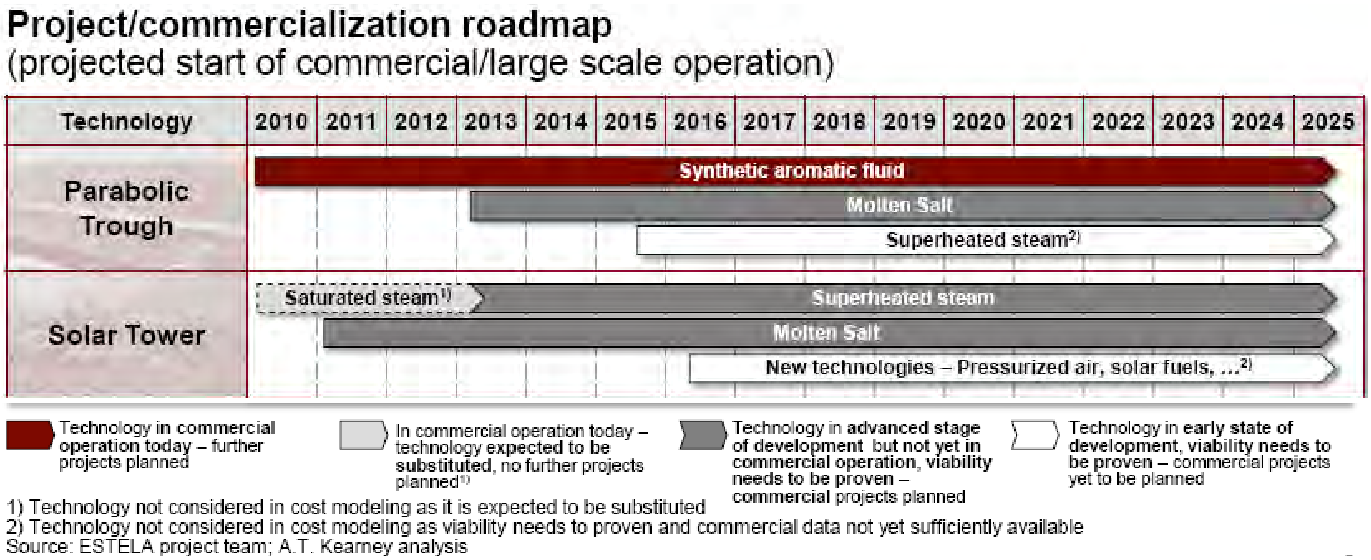


Figure 18. Projected evolution of technologies from the heat transfer fluid point of view.

(Source ATKEARNEY-ESTELA)

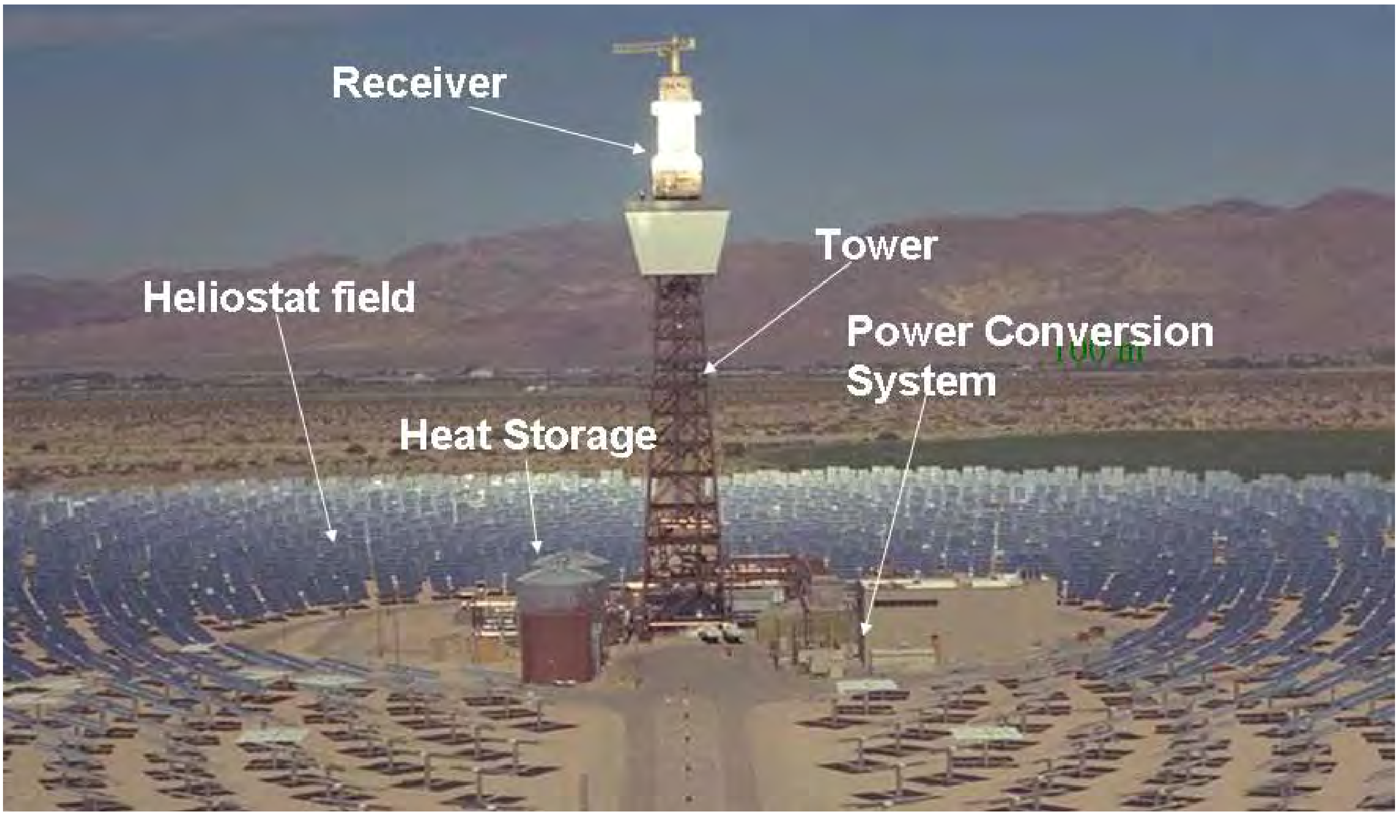


Figure 19. Basic Components of Central Receiver CSP (CR-CSP)

Central Receiver Systems have a large potential for mid-term cost reduction of electricity produced since they allow many intermediate steps between the integration in a conventional Rankine cycle up to the higher exergy cycles using gas turbines at temperatures above 1000°C, and this subsequently leads to higher efficiencies and larger throughputs.

The typical optical concentration factor ranges from 200 to 1000 (times the DNI) and plant sizes of 10 to 200 MW are chosen because of economy-of-scale constraints, even though advanced integration schemes are claiming economic sense for smaller units as well. The high solar fluxes impinging on the receiver (average values between 200–1000 kW/m2) allow working (with high efficiencies) at relatively high temperatures up to 1000°C and to integrate thermal energy into more efficient cycles in a step-by-step approach. CRS can easily integrate in fossil plants for hybrid operation in a wide variety of options or have the potential to generate electricity with high annual capacity factors by using thermal storage. With storage, CRS plants have the capability to operate more than 6000 hours per year at nominal power. Main characteristics of CRS plants are summarized in Table 3. Characteristics of solar thermal power central receiver systems (From Romero et al, 2002).

Typical Size	10–200 MW*
Operating Temperature	
- Rankine	565°C
- Brayton	800°C
Annual Capacity Factor	20–77%*
Peak Efficiency	16–23%*
Annual Net Efficiency	12–20%*
Commercial Status	Scale-Up Demonstration (10–30 MW)
Technology Development Risk	Medium
Storage available	Nitrate salt for molten salt receivers Ceramic bed for air receivers
Hybrid designs	Yes
Investment cost	
$\$.W^{-1}$	4.4–2.5*
$\$.W_p^{-1}$**	2.4–0.9*

*Values indicate changes over the 1997–2030 time frame.
**$\$.W_p^{-1}$ removes the effect of energy storage or solar multiple, as usually made in PV.
(In the present study a conversion rate of 1 Euro=0.91 $ as of September 2001 has been used)

Table 3. Characteristics of solar thermal power central receiver systems (From Romero et al, 2002).

The first commercial solar tower plant (see PS10 Final Technical Report, 2006) uses water as the heat-transfer fluid (HTF) and generates saturated steam (at about 250-280 ºC) to power its turbine. The nexts step in the CRS technology improvement is based in higher temperatures at the receiver outlet either by superheated steam (at temperatures of 400-500 ºC) and molten nitrate salts with outlet temperatures from receiver of 560ºC. A promising pre-commercial concept that is currently under development uses compressed air as the heat transfer medium in combination with a gas turbine. In this case, the receiver replaces the combustion chamber of a conventional gas turbine. In the long run, high solar efficiencies in combination with a combined cycle—i.e., a combined gas and steam turbine cycle—are possible.

The typical size of solar tower plants usually ranges from 10 MWel to 100 MWel. The larger the plants are, the greater is the absolute distance between the receiver and the outer mirrors of the solar field. This induces increasing optical losses due to atmospheric absorption as well as unavoidable angular mirror deviation due to production tolerances and mirror tracking. In addition to the Spanish company Abengoa Solar, which developed, installed, and operates the solar tower technology PS10 and PS 20 shown in Figure 20, several new solar tower technologies have been developed in the last few years and are currently being proven in prototype power plants by the companies BrightSource Energy, Sener, eSolar, and Aora. Among these, the Gemasolar Power Plant (see Figure 21), designed by Sener and owned by Torresol, has been connected to the grid on 1st of May, 2011. It may constitute a breakthrough in the CSP reduction costs since it offers 2% higher overall efficiency (about 16%) and very large heat storage (up to 15 hours).

Recently, Torresol announced the construction of four 50 MWe (200 MWe in total) Central Receiver plants, with the Gemasolar technology, to be developed in Spain starting before 2013.

BrightSource Energy (using a similar technology to Gemasolar, based on molten salts as HTF) entered into a series of power purchase agreements with Pacific Gas and Electric Company in March 2008 for up to 900 MW of electricity, the largest solar power commitment ever made by a utility. BrightSource is currently developing a number of solar power plants in Southern California, with construction of the first plant planned to start in 2009.

In South Africa, a 100 MW solar power plant is planned with 4000 to 5000 heliostat mirrors, each having an area of 140 m². A site near Upington has been selected.

So the Central Receiver is gaining impulse. Thus we have selected a reference plant similar to Gemasolar to assess its costs and electricity production in this study.

1.4.4. Some Commercial Central Receiver CSP plants under operation

Figure 20. PS10 (connected in March, 2007) and PS20 (connected in 2009) CSP-CR plants (in Seville, Spain).

Figure 21. Gemasolar (connected to the Grid the 1rst of May of 2011)

Figure 22. eSolar's 5 MW Sierra SunTower facility located in California.

eSolar unveiled Sierra SunTower in the summer of 2009, a 5 MW plant located in Lancaster, California about 80 km (50 miles) northeast of Los Angeles (Figure 22). The project site occupies approximately 8 hectares (20 acres) in an arid valley in the western corner of the Mojave Desert at 35° north latitude. Sierra SunTower is interconnected to the Southern California Edison (SCE) grid and is the only CSP tower facility operating in North America.

1.4.5. Technology comparison

Each technology has its own value proposition and therefore different deployment optima.

	Parabolic Trough	Solar Tower	Dish Stirling	Linear Fresnel
Value proposition	• **Commercially proven** and **bankable technology** • **Maturity level** and **operational experience** • **Modularity** • Large **number of EPC providers**	• **Commercially proven** and **bankable technology** • **Efficiency** • **High operating temperatures**	• **Modularity** • **Efficiency** • **Low water consumption**	• Cost effective for **steam generation** • **High land-to-electricity ratio** • **Usability of space below support structure** due to linear design
Application/ deployment focus	• **Centralized grid access** locations • Locations with **hybridization possibilities**	• **Centralized grid access** locations • Locations with **hybridization possibilities**	• **Decentralized off-grid power systems** • Locations with **water scarcity** • **Centralized grid access** locations	• **Centralized grid access** locations • Locations with **hybridization possibilities** • Industrial **location** with **steam processing needs**

Figure 23. Qualitative CSP Technologies comparison. (Source: ESTELA project team; A.T. Kearney analysis)

1.5. Actual Costs and perspectives of the CSP Technology

Although CSP technological improvements present a significant opportunity for improving economies of CSP projects, cost evolutions are not solely dependent on technology. Uncertainty of future projects and business instability leads both 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.

Almost all CSP plants are located in Southern Spain and in the US Southwest. Spain has standardized on 50 MW plants. Studies indicate that optimal CSP plants have capacities of 150-250 MW. These plants would have lower capitals cost per kW. Capital investment for solar-only reference systems of 50 MWe without storage are currently in the order of 4 000 €/kWe, varying from 3000 to 5 000 €/kWe. With storage, prices can go up significantly. Three companies are planning 26 plants, each rated at 50 MW, with storage at a capital cost of about 6,000 euro/kW.

Depending on the Direct Normal Irradiance (DNI), the cost of electricity production for parabolic trough systems is currently of the order of 17– 23 c€/kWh (for Southern Europe, the DNI is 2000 kWh/m2/a). For DNI in the range of 2,300 or 2,700, as encountered in the MENA region or in the USA, the current cost could be decreased by 20 to 30% (Figure 24). For a given DNI, cost reductions of the order of 25 to 35% for parabolic trough plants is achievable due to technological innovations and process scaling up to 200 MWe.

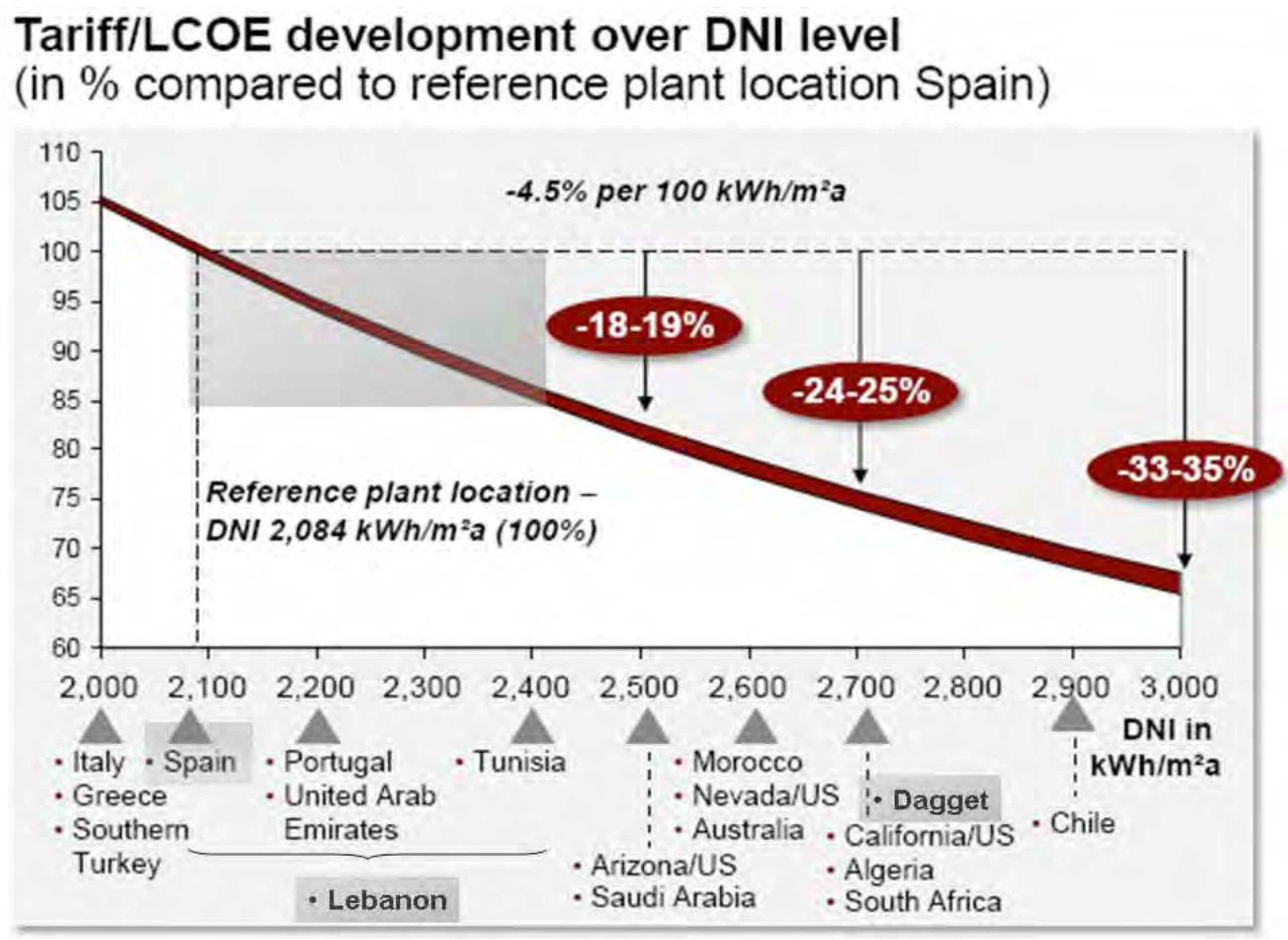


Figure 24. Correlation among DNI and CSP electricity cost (from ATKEARNEY, 2010 and author processing)

According to the ESTELA Roadmap study (ATKEARNEY, 2010): "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. (See Figure 25)

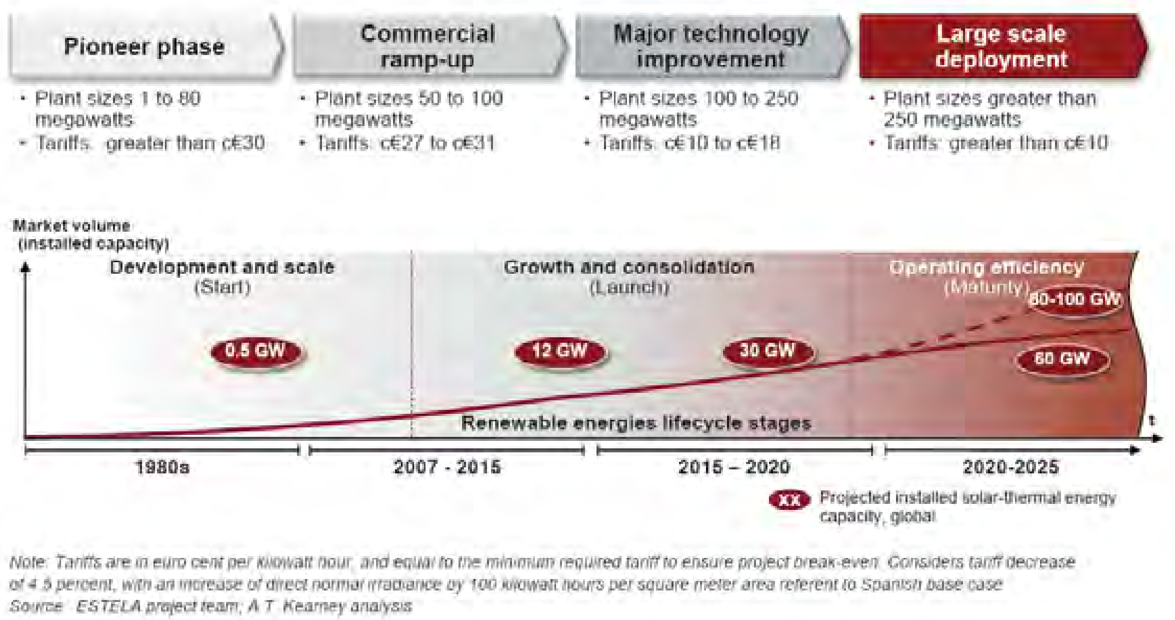


Figure 25. Projected roadmap for CSP electricity costs with power implementation (according ATKEARNEY-ESTELA, 2010).

"In the longer term, to make concessional finance less critical, generation costs will need to be dramatically lower. This implies that investment costs, and therefore manufacturing costs of the main components and systems, need to decrease. It will be made possible by a combination of technical innovation, economies of scale, and experience curve effect. The potential for such cost decrease is considerable, as CSP is a young industry, with a limited number of large or experienced players".

"The **CSP industry is committed to technological improvement initiatives**, focused on increasing plant efficiency and reducing deployment and operating costs. **By 2015**, when most of these improvements are expected to be implemented in new plants, **energy production boosts greater than 10% and cost decreases up to 20% are expected to be achieved"**.

"*Furthermore, economies of scale resulting from plant's size increase will also contribute to reduce plants' CAPEX per MW installed up to 30%. CSP deployment in locations with very high solar radiation, such as the MENA region, further contribute to the achievement of cost competitiveness of this technology by reducing costs of electricity up to 25%.*

All these factors can lead to electricity generation cost savings up to 30% by 2015 and up to 50% by 2025, reaching competitive levels with conventional sources (e.g. coal/gas with LCOE <10€c/kWh)".

The economical potential of CSP electricity in Europe (EU-27) is estimated to be around 1,500 TWh/year, mainly in Mediterranean countries (DNI > 2000 kWh/m2/year) (DLR, 2005 and Salazar, 2008). Based on today's technology, the installed capacities forecasted in the EU-27, under the European Solar Industry Initiative are 830 MW by 2010, 30 GW by 2020 and 60 GW by 2030 [ESTELA, 2009]. This represents respectively up to 2030, 0.08%, 2.4% and 4.3% of projected EU gross electricity consumption. These penetration targets do not account for imports of CSP electricity.

Regarding the DESERTEC scenario, which assumes that a grid infrastructure will be built within the Northern African countries, CSP electricity imports of 60 TWh in 2020 and 230 TWh in 2030 could be realised [Desertec, 2009]. The penetration of CSP electricity for 2030 under these scenarios would be 10% of the EU gross electricity consumption. Scenarios for the worldwide deployment of CSP technology vary significantly between the 2008 IEA Energy Technology Perspective scenario and the Greenpeace/European Renewable Energy Council Scenarios [IEA, 2008 and GreenPeace, 2008].

The IEA scenarios range between less then 10 GW installed capacity or less then 15 TWh (Baseline) to 250 GW (ACT and Blue Scenarios) or 625 TWh (ACT) and 810 TWh (Blue) in 2030. The European share would be about 15%. No figures for 2010 and 2020 are given. On the other hand, the Greenpeace scenarios vary between 2 GW (5 TWh) by 2010, 8 GW (26 TWh) by 2020 and 12 GW (54 TWh) by 2030 for the reference scenario; 5 GW (9 TWh) by 2010, 83 GW (267 TWh) by 2020 and 199 GW (1,172 TWh) by 2030 for the [r]evolution scenario; and 5 GW (9 TWh) by 2010 100 GW (320 TWh) by 2020 and 315 GW (1,860 TWh) by 2030 for the advanced scenario. The European industry has currently a market leadership in CSP technologies worldwide. At this stage of development, there is a supply chain industry already able to offer turn-key equipments for power plants in the range of 10 to 50 MW. However, an industrial ramp-up in all aspects (engineering, procurement and construction, components, manufacturing, maintenance) will be necessary to go from current market shares to significant ones.

1.6. Is CSP technology sufficiently mature for Lebanon?

This report cannot give a clear answer to this question but will provide qualitative and quantitative information for clarifying the issues required to answer this question. The answer to that key question will depend on the assessment criteria and the point of view adopted; We could distinguish several point of views to approach the answer which we have tried to feed with information in this report:

- **From a Technical point of view**: in 2011, there are sufficient commercial plants already built to find feasible (low risk) solutions within a variety of CSP typologies, power sizes, etc.
- **From an Economical point of view**, CSP continues having high investment and production costs. Low costs of fossil fuels remain an important barrier on grid – even more so in countries where fossil fuels prices are kept below world prices by direct or indirect government subsides. Investment costs range from USD 4.2 to 8.4 per watt, depending on the solar resource and the size of the storage. Levelised electricity costs range from US cents 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:
    - o 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)
    - o 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)
    - o Similar values (in investment and LEC) for Central Receiver CSP plants.
- **From other points of view** (Social, Environmental, Political, …):

  Growth drivers for CSP include increasing demand for Renewable Energy Sources (RES) complemented by its **unique value proposition** when **compared with other energy sources:**

    - o Predictability and reliability of production
    - o **Dispatchability** due to proven and highly cost efficient storage and potential plant integrated back up firing
    - o **Grid stability** due to the inertial features of STE power blocks
    - o **Cost competitiveness** against other renewable energy sources

- o Large scale deployment and energy on demand
    - o Long-term supply security and independence from oil and gas prices
    - o High share of local content
    - o The building of a CSP plant creates eight to ten Jobs per megawatt electrical solar capacity in the construction and manufacturing of components.
    - o **Possibility to deal with water scarcity either by implementing schemes of plant with dry cooling or even using part of the waste heat for desalinization of sea water**
    - o Possibility to obtain GEF grants?

1.7. Which new driving forces may we identify to foster the viability of CSP in Lebanon?

Since the ESCWA report other roadmaps and assessment reports for CSP on the MENA region have appeared. We must mention the "Status and Potentials of Renewable Energy Technologies in Lebanon and the Region (Egypt, Jordan, Palestine, Syria) - GREEN Line Association (of Feb. 2007)" which assess the maturity of CSP for Lebanon stating (page 13):

…Needless to say, none of the options under development today such as solar towers and solar concentrators are installed or even being considered at any level as a means to produce electricity. Without a well-known and established technology, these systems will not be considered for Lebanon…

The 2011 Ernst & Young and Fraunhofer report on: "Middle East and North Africa Region Assessment of the Local Manufacturing Potential for Concentrated Solar Power (CSP)", (commissioned by the World Bank with donor support from the Energy Sector Management Assistance Program (ESMAP)), analyses the potential local manufacturing potential for CSP components in the MENA region. In its "Foreword" it sates:

The Middle East & 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. It is also close to Europe, where green electricity is much valued.

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, concessional finance and export of green electricity to Europe. The MENA CSP scale-up Investment Plan (MENA CSP IP), supported by the World Bank and the African Development Bank (AfDB), is intended to strategically utilize concessional financing from the Clean Technology Fund (CTF) to accelerate global adoption of the technology in the region. It was endorsed by the CTF Trust Fund Committee on December 2, 2009, and will support expansion programs in five countries of the MENA region, Algeria, Egypt, Jordan, Morocco and Tunisia

… 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, as well as existing markets in Southern Europe, in the US and elsewhere. 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.

And in its “Executive Summary” states:

“To run CSP projects in MENA competitively in the short and medium term, a portfolio of different support schemes for CSP plants is necessary, including climate finance and concessional loans, revenues from solar electricity exports to Europe, and national incentives (like long-term power purchase agreements (PPA), feed-in tariffs, or tax rebates)..

“As a concrete step toward realizing these strategies, a —MENA CSP scale-up Investment Plan‖ (MENA CSP IP) was prepared by the World Bank and the African Development Bank (AfDB), and endorsed by the Clean Technology Fund (CTF) Trust Fund Committee on December 2, 2009. This plan is a landmark climate change mitigation program aimed at co-financing nine commercial-scale power plants (totaling around 1.2 GW) and two strategic transmission projects in five countries of the MENA Region (Algeria, Egypt, Jordan, Morocco and Tunisia, called the —MENA CTF‖ countries in the rest of this report). The vision is for the Mediterranean

MENA countries ultimately to become major suppliers and consumers of CSP-generated electricity. The MENA CSP IP is conceived as a transformational program, leading to the installation of at least 5 GW of CSP capacity in MENA by 2020, based on the 1.2 GW triggered by the MENA CSP IP. The first projects are expected to start commercial operations by 2014, and initially to supply domestic markets in MENA countries.

“MENA could become home to a new industry with great potential in a region with considerable solar energy resources. If the CSP market increases rapidly in the next few years, the region could benefit from significant job and wealth creation, as well as from enough power supply to satisfy the growing demand, while the world‘s renewable energy sector would benefit from increased competition and lower costs in CSP equipment manufacturing.

“The transformational opportunity from local manufacturing of CSP in MENA countries could benefit from the following interrelated factors:

- *“MENA CSP is well placed to benefit from the massive scale-up of concessional climate financing envisaged under the United Nations Framework Convention on Climate Change (UNFCCC), and recently reaffirmed at the Copenhagen and Cancun conferences. The CTF allocation for the MENA CSP IP could be the seed money for financing a more ambitious scale-up. CSP in MENA and other regions could benefit from the recent Cancun agreements in 2010 which have opened the way for a much larger funding framework. The climate conference of Cancun agreed on a Green Climate Fund of $100bn a year of climate funding from 2020 onwards that will be generated from a “wide variety of sources, public and private, bilateral and multilateral, including alternative sources.” This could include a range of mechanisms such as auctioning carbon credits and levies on international aviation and shipping.*

- *“MENA CSP is central to the high-level political agreement between MENA and the European Union to make solar energy trade a fundamental pillar of MENA-EU economic integration, and it therefore presents a major opportunity for MENA to earn export revenue. MENA CSP could be key to realizing the EU’s GHG emissions reduction and energy security objectives. The April 2009 EU Renewable Energy Directive, with its provisions for the import of renewable energy to achieve the mandatory renewable energy targets of EU member states, is a first step in that process, as are the Desertec Industry Initiative and the Transgreen/Medgrid Initiative. The political initiative of the Mediterranean Solar Plan may act as an umbrella for initiatives such as Desertec at a bilateral level.*

- *“MENA’s oil-producing countries are embarking on CSP investment programs to liberate oil and gas from the power sector for higher value-added uses and exports, and in the longer term for CSP energy export.*

"The combination of these factors could uniquely advantage MENA as a global location of choice for CSP production and, while creating demand for installed capacity, could strongly drive local manufacturing.

Nevertheless, besides the CEDRO-UNDP Project which originates the actual study, we identified a renewed interest on CSP for Lebanon, starting by

> "*A call for U.S. companies to develop a feasibility study for a 50 megawatt (MW) Concentrated Solar Power (CSP) plant in Lebanon has been made by the United States Trade and Development Agency (USTDA) and Lebanon's Zeenni's Trading Agency, in light of continued energy shortages in the country. The agencies say the feasibility study would follow the success of the solar thermal industry and develop a plan for effectively implementing CSP technology in the Byblos region, with good potential to replicate this technology in other areas. It is hoped the study will assess CSP technology and analyze the construction of a 50 MW CSP power plant*"

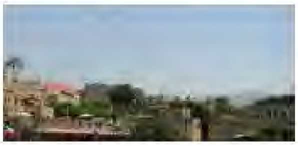
(see below the article in the pv-magazine.com)

pv-magazine.com

Lebanon looks to expand CSP activities in light of electricity shortages

22. JUNE 2010 | MARKETS & TRENDS, APPLICATIONS & INSTALLATIONS, TOP NEWS | BY: BECKY STUART

A call for U.S. companies to develop a feasibility study for a 50 megawatt (MW) Concentrated Solar Power (CSP) plant in Lebanon has been made by the United States Trade and Development Agency (USTDA) and Lebanon's Zeenni's Trading Agency, in light of continued energy shortages in the country.



A plan is to be developed for effectively implementing CSP technology in the Byblos region. Image: Wikipedia/Magnus Manske.

The agencies say the feasibility study would follow the success of the solar thermal industry and develop a plan for effectively implementing CSP technology in the Byblos region, with good potential to replicate this technology in other areas. It is hoped the study will assess CSP technology and analyze the construction of a 50 MW CSP power plant.

They say that despite large government investments in the power sector, demand still exceeds supply, and blackouts are common in peak demand times. Renewable energy currently plays a minor role in the energy mix in Lebanon. However, they continue, the country experiences over 300 days of sunshine a year, making solar energy one of the better alternatives for a renewable energy source.

The agencies go on to say that increasing renewable energy sources is a policy priority for the Government of Lebanon, as the country imports nearly 99 percent of its energy due to a lack of indigenous sources. High costs and insufficient supplies have lead to frequent electricity outages, they continue, which have resulted in "significant damage" to the economy and the tourism industry.

The study will include an analysis determining the best CSP technology to use; a techno-economic assessment; engineering, procurement and construction cost estimates; and a project implementation plan for a 50 MW CSP power plant. The U.S. firm selected will be paid in U.S. dollars from a $338,270 grant to the Grantee from the USTDA.

www.pv-magazine.com

2. Techno-economic assessment of CSP plants for Lebanon.

2.1. *Analysis objectives and Choice of Reference Systems*

The objectives for the analysis is to assess the cost and performance of the more mature CSP technologies in a good placement of Lebanon and to compare these cost and performances with the reported (and here evaluated) figures for a site in South of Spain and a site in South-west of United States where more that 95% of the CSP plants and projects are being developed.

This analysis will provides a set of details of CSP pre-design and some estimates of cost that could help in this CSP feasibility for Lebanon assessment phase.

The **three selected localities** (having different annual DNI levels) and sources of meteorological data are the following:

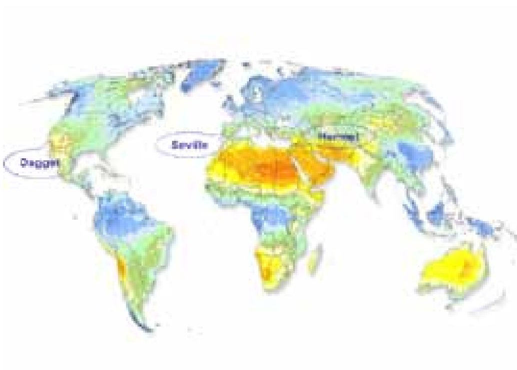
1) Seville (Spain) [2017 kWh/m2/year].(The source of this data is the meteorological measurements used in the pre-design of the PS10 plant)

2) Hermel (Lebanon) [2445 kWh/m2/year]. (The meterological data for Hermel comes from synthetic generation by using the Meteonorm code. "*Meteonorm* is a comprehensive meteorological reference, incorporating a catalogue of meteorological data and calculation procedures for solar applications and system design at any desired location in the world. It is based on over 25 years of experience in the development of meteorological databases for energy applications". http://meteonorm.com/)

3) Dagget [USA] or a locality in MENA > 2600 kWh/m2/year (Data for Dagget are measurements available in the System Advisor Model, SAM, from NREL: https://www.nrel.gov/analysis/sam/)

Table 4 Total DNI of the meteorological data sheets used for comparison

Locality	SEVILLE	HERMEL	DAGGETT
State	Spain	Lebanon	CA (USA)
daily avrg. DNI (Wh/m2)	238.5	279.1	318.7
Annual DNI (kWh/m2/year)	2 089	2 445	2 792
Latitude	37.42	34.39	34.87
Longitude	-5.9	36.39	-116.78
Time zone	2	3	-8



What changes from one locality to other?

- Resource (see Table 4)
- Optical efficiency of solar field (e.g.: design of solar field is dependent of latitude and performance of cycles is dependent on temperatures)
- Costs (f.i.: labor cost for operation and maintenance, etc.)

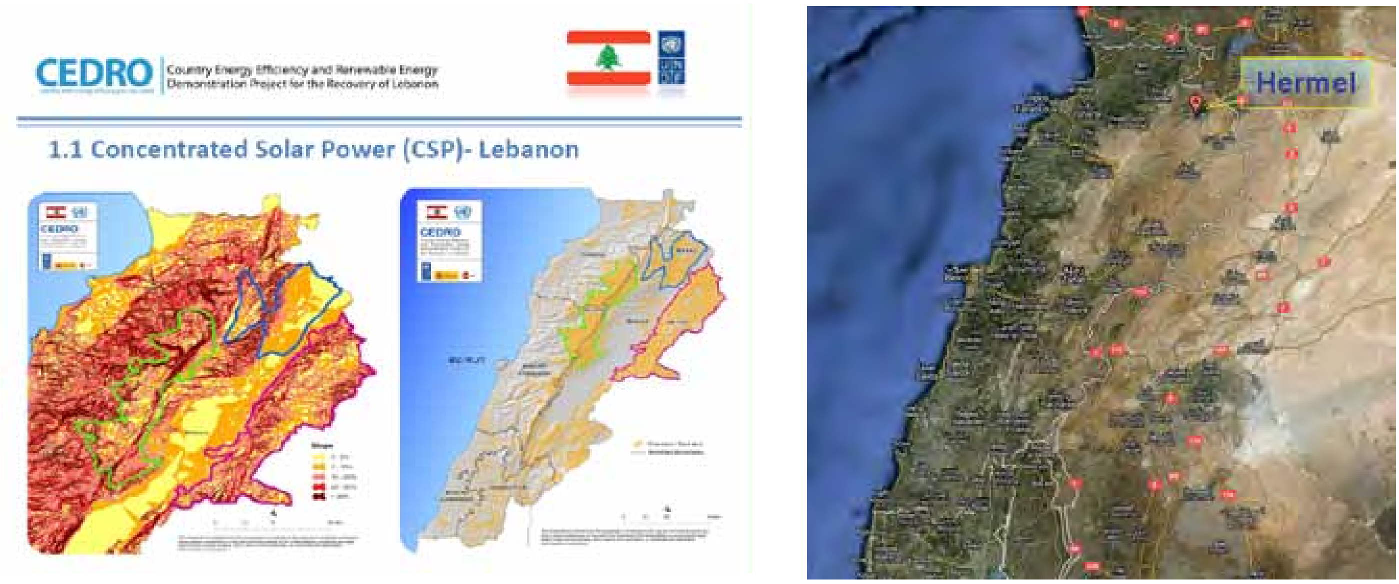


Figure 26. Choice of Hermel (Lebanon) within the candidate region pre-selected by CEDRO due to its high solar resource for CSP feasibility assessment.

To select the reference CSP plants to analyse its comparative costs and performances in the three sites**, two main criteria have been used**:

1) Commercial availability or **Technological maturity**: The reference CSP plants to assess should be chosen among the most mature CSP. This criteria leads to chose Parabolic Trough using synthetic oil as HTF. The addition or not of a Heat storage lead to options: with and without heat storage
2) **Similar sizes as the Spanish commercial CSP power plants** (about 20 to 50 MWe or total investments in the order of 100 to 300 M€). These sizes are not the optimum for CSP in terms of overall efficiencies but implies reduced economical risk.

Thus, the combination of both criteria leads to the following **list of Reference CSP Plants to compare** as feasible for Lebanon:

1. A Parabolic Trough Plant with 7.5 hous of heat storage, (like Andasol and other 30 plants in Spain),
2. A PT Plant **without** heat storage (as about 10-13 plants in Spain)
3. A central receiver CSP plant using molten nitrate salts and **large heat storage** (like Gemasolar –already connected- and about other 400 MWe of projects in Spain and USA).
4. A Central Receiver CSP plant using saturated water steam as HTF with negligible heat storage, of about 0.5 hours. (Like PS20, in operation since 2009).

2.2. Methodology

Today several CSP technologies (like parabolic troughs and central receiver using different heat transfer media) are under commercial deployment for bulk power production mainly in Europe and in United States, but also in other regions as North Africa and Middle East, China, India and Australia. Those technologies which have achieved a status of enough maturity to be chosen for significant deployment are considered in this analysis.

The approach is to perform a comparative techno economical analysis of the chosen technologies in several locations with different resource levels and different geographical coordinates.

Total Cost and annual performance information of the reference systems are in the order of the figures confirmed by the industry. For the cost of the components, which use to be kept confidential by the Plant promoters, that figures are estimated according to our best knowledge.

The methodology for the cost study uses as main figure of merit is the Levelised electricity cost (LEC) which is calculated according to a simplified IEA Method[1] (see figure 28, where the common assumptions for the financial parameters are listed, too). The approach is kept simple, but it appears to be appropriate to perform a relative comparison, necessary to quantify the electricity costs for this assessment.

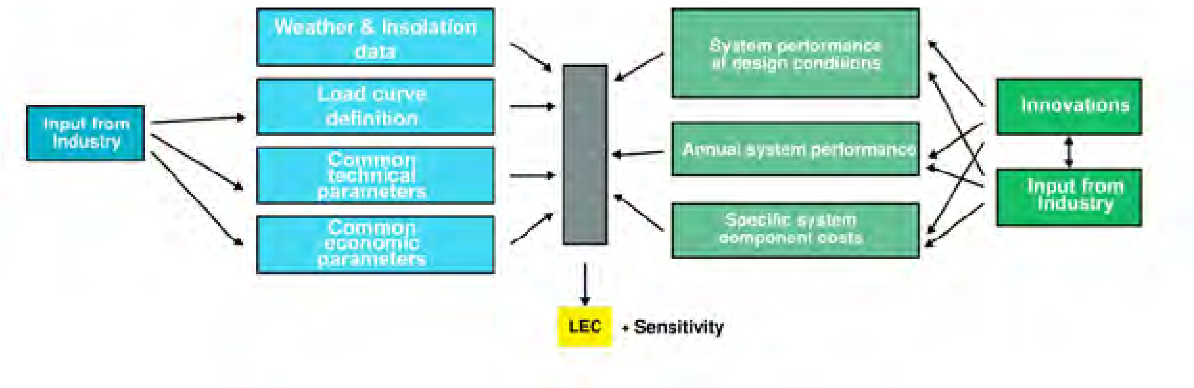


Figure 27. Methodology for analysis

Definition of "Levelized Electricity Costs" (LEC)

$$LEC = \frac{crf \cdot K_{invest} + K_{O\&M} + K_{fuel}}{E_{net}}$$

with

$$crf = \frac{k_d(1+k_d)^n}{(1+k_d)^n - 1} + k_{insurance} = 9{,}88\%$$

k_d real debt interest rate = 8%

$k_{insurance}$ annual insurance rate = 1%

n depreciation period in years = 30 years

K_{invest} total investment of the plant

$K_{O\&M}$ annual operation and maintenance costs

K_{Fuel} annual fuel costs

E_{net} annual net electricity

Figure 28. Levelized Electricity Cost (LEC) formula.

For each reference system a complex performance and economic model has been established in Microsoft Excel. The model is based on common assumption on the site, meteorological data and load curve. It calculates the annual electricity production hour by hour, taking into account the instant solar radiation, load curve, part load performance of all components (depending on load fraction , ambient temperature and incident power over receiver) operation of thermal energy storage as well as parasitic energy requirements.

Input data for the reference cases were partly provided by the industry consortium and taken from literature.

[1][1]International Energy Agency (IEA), Guidelines for the economic analysis of renewable energy technology applications, 1991.

2.3. Parabolic Trough Reference Systems.

Almost 30 CSP plants similar to Andasol-1 power plant are being developed in Spain with 15 already connected to the electrical network. So the Andasol-1 may be used as a reference to assess for Lebanon.

With the same engineering project, three parabolic trough power plants have been built on the plateau of Guadix in the province of Granada/Spain: Andasol 1,2 and 3 (Figure 13). They produce 50MW of electricity each and they will use parabolic trough technology with synthetic oil as heat transfer fluid. The plants are equipped with thermal energy storage, in order to provide power even in times without sunshine. The storage technology is based on the two-tank molten salt system, which is coupled to the heat transfer fluid via an oil-salt heat exchanger. When the solar field delivers heat in excess to the amount needed by the power block, this heat may be used to charge the storage. The solar field will be oversized with respect to the nominal thermal input of the steam turbine.

“Andasol is the first parabolic trough power plant in Europe, and Andasol 1 went online in March 2009. Because of the high altitude (1,100 m) and the semi-arid climate, the site has exceptionally high annual direct normal irradiation of 2,200 kWh/m² per year. Each plant has a gross electricity output of 50 megawatts (MWe), producing around 180 gigawatt-hours (GW·h) per year (21 MW·yr per year). Each collector has a surface of 51 hectares (equal to 70 soccer fields); it occupies about 200 ha of land”.

Table 5 Main characteristics of the Andasol type power plants

Data about the Anadasol-power plants(Data per power plant)	
Location	
Project names	Andasol 1, Andasol 2, Andasol 3
Location	10 Km east of Guadix in the municipal area of Aldeire and La Calahorra in the Marquesado del Zenete región , Granada Province
Terrain	Approx. 195 hectares (1300m x 1500M), North-South Axis
High-voltage line Access	Connection to the 400KV line near Hueneja (about 7 KM away)
Solar Field	
Prabolic trough technology used	Skal-ET
Size of the solar field	510,120m²
Number of parabolic mirrors	209,664 mirrors
Number of receivers(absorbtion pipes)	22,464 pipes each measuring 4 m
Number of solar sensors	624 sensors
Annual direct standard radiation(DNI)	2,136 KWh/m²a
Solar field efficiency	approx. 70% peak efficiency, approx. 50% annual average
Heat storage capacity	28,500 t salt for 7.5 peak load hours
Power plant capacity	
Turbine capacity	49.9 MW
Annual operating hours	ca. 3.500 Volllaststunden
Forecast gross electricity volume	about 180 GWh
Efficiency of entire plant	approx. 28% peak efficiency, approx. 15% annual average
Estimated lifespan	at least 40 years

The power block consists of a Rankine cycle with a reheat steam turbine. The upper temperature of the heat transfer fluid is limited to approximately 395°C due to the decomposition of the synthetic oil and the stability of the selective coating of absorber tubes. Details on the plant reference data are given in http://en.wikipedia.org/wiki/Andasol_Solar_Power_Station. and (Solar Millennium, 2008).

“Andasol 1 cost around €300 million (US$380 million) to build. The developers say Andasol’s electricity will cost €0.271 per kilowatt-hour (kW·h) to produce. The thermal energy storage at 380 degrees ºC (75 tonnes of salt per MWhe) costs roughly US$50 per kilowatt-hour of capacity, according to Greg Glatzmaier of the U.S. National Renewable Energy Laboratory (NREL) — about 5% of Andasol’s total cost.

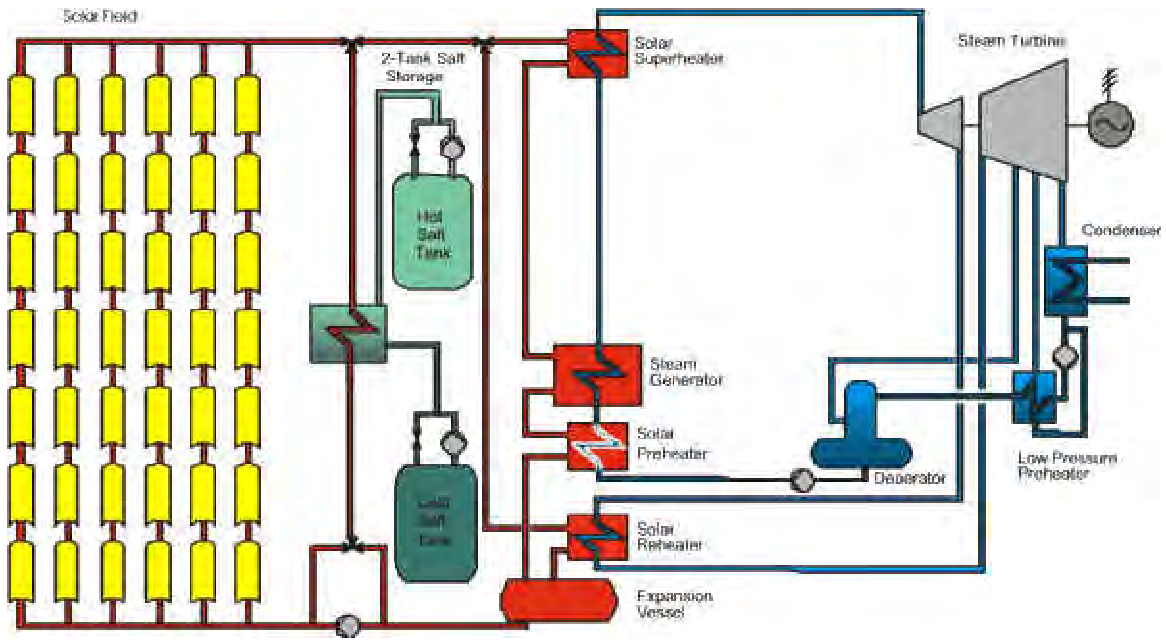


Figure 29 Operational scheme of the AndaSol power plants [1]

Like every power plant with thermal engine cooling is needed here, too. As Andasol is built in the warm middle of the south of Spain, every Andasol-unit vaporizes 870.000 m³ water per year (as specified by the manufacturer), that means converted 5 l/KWh or 1.2 gal/KWh . Conventional power plants need less (2.5 l/KWh) or don't have this problem, as they can be built in cooler regions, can be cooled by percolation or use seawater at the coast. Although water supply is generally a problem in Spain, the position of Andasol (Sierra Nevada) supplies enough water.

Developers: "The developer of the Andasol 1 and Andasol 2 plants are Solar Millennium (25%) and ACS Cobra (75%). After planning, engineering and construction Solar Millennium sold their shares to ACS Group. Andasol 3 is developed by the consortium of Solar Millennium and MAN Ferrostaal. Marquesado Solar SL is the investor consortium which is going to commission and operate Andasol 3. Shareholders of Marquesado Solar SL are:

- Solanda GmbH, a joint venture of Solar Millennium and MAN Ferrostaal AG (26%)
- Stadtwerke München (48.9%)
- RWE Innogy & RheinEnergie AG (25.1%)

2.3.1. Cost and performance of PT reference systems

Based on these reference data, we have pre-designed two PT power plants (WITH and WITHOUT heat storage) for the three selected sites, load curve and other boundary conditions with the lowest solar LEC according to our model. Further optimization in a more detailed model may result in slightly different configuration or cost figures. However, the degree of detail of the used model appears sufficient to analyze the overall impact of changes in cost and performance. Although some input parameters, for a given reference system may change with the plant placement, most of these inputs parameters are maintained for the three sites.

The input parameters for the pre-designed PS reference plants may be found in the next (Table 6) and (Table 7).

Table 6: Technical Input parameters for Parabolic Trough Reference Systems.

Technical Input Parameters	Units	PT - 50 MW + 7.5 h storage (As ANDASOL)	PT - 50 MW + NO storage (as SEGS) -
Solar Field			
Site		Hermel	Hermel
Longitud		36.39	36.39
Latitude	°	34.39	34.39
Time zone	-	3	3
Solar Multiple		**1.99**	**1.05**
Direct Normal Irradiation	kWh/m2/y	2445	2445
Total Aperture Surface	m2	509 440	268 800
Required Ground Surface	km2	1.99	1.05
Length of a Single collector	m	150	150
focal length	m	2.22	2.22
collector row spacing / aperture width	-	3	3
Annual Mean Reflectivity of the mirrors	-	0.88	0.88
Optical Peak Efficiency (design point)		0.7	0.7
HTF temperature at field entrance	°C	291	291
HTF temperature at field exit	°C	391	391
design parasitics for pumping and tracking (total)	kW	4 993	3 011
threshold angle for sunrise/sunset	(grades)	7	7
Heat transfer and Power Block			
Heat loss factor piping	W/m²	0.02	0.02
Design Net Electrical Output	kW	50 000	50 000
Design Efficiency of the Power Block (nominal conds.)	-	0.381	0.381
Storage Capacity (nominal hours)	h	7.5	0.0
Thermal Capacity of the Storage	kWh	1 082 530	1 391
Storage efficiency		0.95	0.95
HTF temperature in storage discharging	°C	371	371

The reference plants were designed: 1) with a 1.99 times larger solar field than needed to provide the design power (solar multiple = 1.99) and about 7.5 hours storage in the case of a rather dispatch able plant, like Andasol type; and 2) with a 1.05 times larger solar field than needed to provide the design power (solar multiple = 1.05) for the case of parabolic trough plant without heat storage (less dispatch able). As it may be seen in Table 6 this leads to quite different solar field aperture: abut 500.000 m2 in case of plant with 7.5 of heat storage and, about 270.000 m2 (for the Hermel used DNI) for the case of parabolic trough without heat storage.

Table 7: Cost Input parameters for Parabolic Trough Reference Systems.

O&M Input	Units	PT - 50 MW + 7.5 h storage (As ANDASOL) in Hermel	PT - 50 MW + NO storage (as SEGS) in Hermel -
Labor costs per employee	€/ year	30000	30000
number of persons (without field maintenance)		25	25
spec. number of persons for field maintenance	1/1000m²	0.030	0.030
number of persons for field maintenance		15.3	8.1
Water costs per MWh electricity produced	€/MWh	1.30	1.30
O&M Equipment costs percentage of investment	per a	1%	1%
Specific Fix O$M cost associated to the Power Block	€/kWe	27	27
Specific Variable O$M cost associated to the Power Block	€/MWh	2.5	2.5
Cost input			
Specific investment cost for solar field	€/m2	220	220
Specific investment cost for power block	€/kW_e	1500	1500
Specific Investment Cost for Heat Storage	€/kWh_th	40	40
Specific Cost for civil works	€/m2	10	10
Auxiliary Gas Burner cost	€/kWth	42	42
Fuel cost for hybridization	€/MWh	15	15
Mean price of conventinal electricity	€/MWh	40	40
Financial parameters			
annual Insurance cost		1.0%	1.0%
Life time	years	30	30
dept interest rate (kd)		6.00%	6.00%
surcharge for construction		10%	10%
surcharge for engineering & management		5%	5%
surcharge for contingencies		5%	5%

The labor costs per employee have been assumed different for Lebanon (30.000 €/year) that for Spain and California (48.000 €/year).

The Financial parameter affect very much to the cost of electricity produced. For centering the assessment on the optional technologies, we have assumed reasonable (at least for Spain), and equal for all the technologies, financial parameters.

The cost Inputs for equipment are approximated and coincident with the figures used in the Spanish projects.

Using the modeling in hourly base we have found the technical and economical results that are shown in the next tables.

Table 8. Technical Results for PT reference systems

		PARABOLIC TROUGH (WITH HEAT STORAGE)			PARABOLIC TROUGH (WITHOUT HEAT STORAGE)		
Technical RESULTS	**Units**	**PT - 50 MW + 7.5 h storage (As NDASOL) - SEVILLE**	**PT - 50 MW + 7.5 h storage (As NDASOL) - HERMEL**	**PT - 50 MW + 7.5 h storage (As NDASOL) - DAGGET**	**PT - 50 MW + NO storage (as SEGS) - SEVILLE**	**PT - 50 MW + NO storage (As SEGS) - HERMEL**	**PT - 50 MW + NO storage (As SEGS) - DAGGET**
Annual Net Electricity Output	**MWh**	142 555	170 589	188 301	84 092	88 643	99 326
Annual (solar-only) Gross Electricity produced	MWh	159 968	191 034	210 809	96 806	102 150	114 929
NET Electricity Production using 15% hybridization with Gas	**MWh**	167 711	200 693	221 530	98 932	104 285	116 854
Gross Electricity Production using 15% hybridization with Gas	MWh	188 198	224 745	248 011	113 889	120 176	135 210
Parasitics	MWh	12075	14472	15962	7390	7803	8757
TOTAL DNI incident on Aperture	%	1 026 583	1 245 702	1 393 479	619 045	657 280	750 335
Annual efficiency Solar Field	%	50.61%	49.09%	48.64%	50.61%	49.09%	48.64%
Annual Mean Efficiency of Receiver	%	78.74%	80.94%	79.73%	78.74%	80.94%	79.73%
Annual Mean efficiency Power Block	%	37.13%	37.21%	37.22%	36.29%	36.26%	36.12%
Annual Gross Efficiency of the Plant	%	15.58%	15.34%	15.13%	15.64%	15.54%	15.32%
Loss of Efficiency due to Parasitics (% of the total eff.)	%	8.47%	8.48%	8.48%	8.79%	8.80%	8.82%
(A1dumping) /(used thermal power)	%	0.00%	0.20%	0.04%	0.73%	0.19%	0.02%
Annual NET Efficiency	**%**	13.89%	13.69%	13.51%	13.58%	13.49%	13.24%
Total Energy passing in Heat Storage	MWh	698 385	1 122 877	1 089 234	434	221	55
Mean Heat Storage Efficiency	%	99.33%	99.38%	99.36%	98.81%	98.79%	98.41%
Annual CAPACITY FACTOR	**%**	38.29	45.82	50.58	22.59	23.81	26.68

Observe that net electricity production for the reference PT plant with 7.5 heat storage hours (of 142 555 MWh as shown above) seems that does not coincide with the above mentioned 180 GWh of electricity production for Andasol.

The fact is that the 180 GWh refers to the electricity that may be sold in Spain which allows a 15% of hybridization (burning fuel Gas). Thus, in Seville, with annual DNI of 2015 KWh/m2/day, the Andasol plant would sold 167.7 GWh a year. But Andasol is located in Guadix (Graada) which has about

2200 kWh/m2/year of DNI, a 10% more that in Seville. Adding this 10% we would justify the ~180 GWh of electricity production for Andasol (see Table 5).

Hybrid operation with a large fossil share was not considered beneficial for this kind of CSP plant, since due to the low cycle efficiency (38.1%). Assuming a boiler efficiency of about 95% and a gas price of 15 €/MWh (based on LHV) solely the fuel costs for the fossil electricity generation would be higher than 40 €/MWh, so that electricity from a fossil "shadow power plant" may be the cheaper approach

Besides, in the results of

Table 8 we may observe (for solar-only operation):

- Annual electricity productions, for PT with 7.5h heat storage, of 142 GWh (for DNI as in Seville), 170 GWh (for DNI as the used for Hermel) and about 188 GWh (for Dagget). The rates of production in the different sites are almost equal to the rates of the annual DNI among sites.
- Annual Capacity Factors varies from 22-27% for the plants without heat storage to 38 -50% for the plants with 7.5 hours of heat storage. This Capacity factor means that, on an annual basis, for the 0 to 24 full load scheme the parabolic trough plant with HTF and a 0 or 7.5 h thermal storage is able to deliver about 22-27% - in case of 0 h- or about 38-50% -in case of 7.5 h- of the demanded electricity from solar heat).
- The Gross overall efficiency of the plants are very similar from site to site (this is mainly due to the fact that the three sites have similar latitudes) varying between 15.3% to 15.6%.
- The NET overall annual efficiencies estimates varies from 13.2% to 13.9%

The cascade of efficiencies for components and overall plant may be also seen in Figure 30.

These overall solar-to-net electric efficiency (of 13.2% to 13.9%) is higher than the plants performance of the existing SEGS plants in California (10.6%) due to an improved collector design (Eurotrough and new absorber tubes) which are commercially available today.

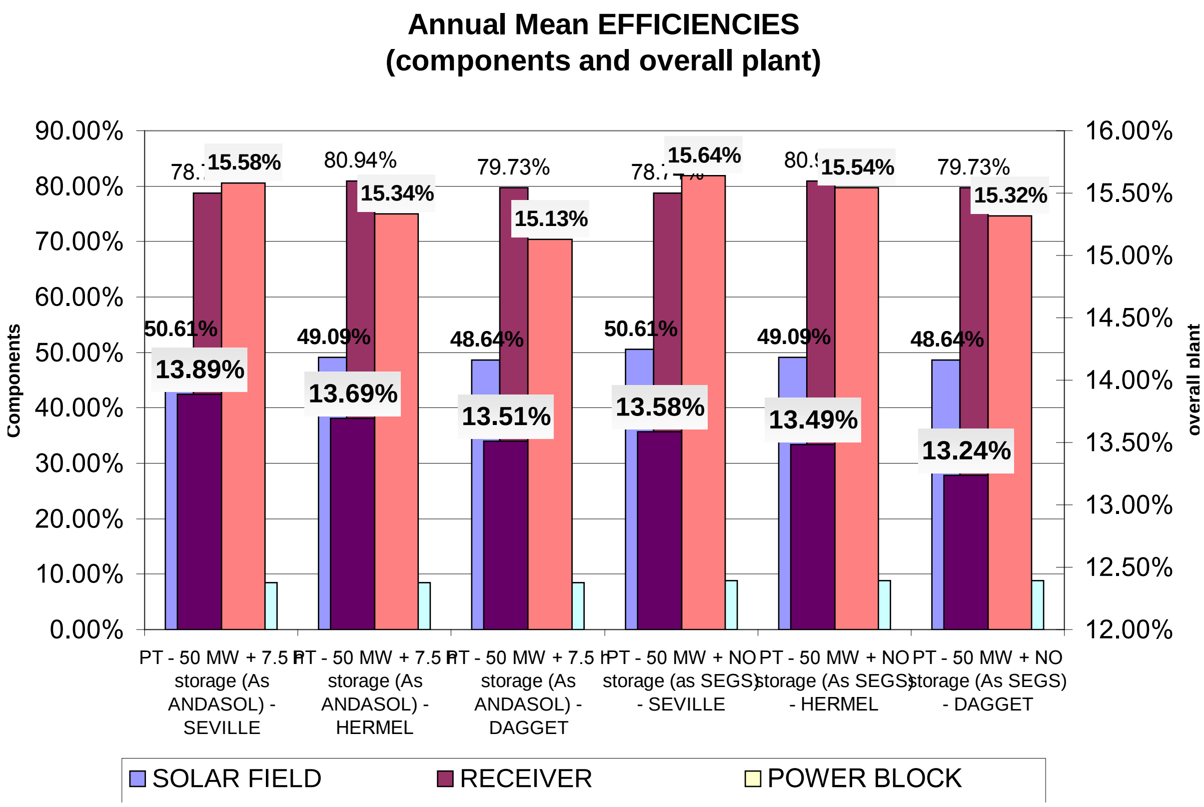
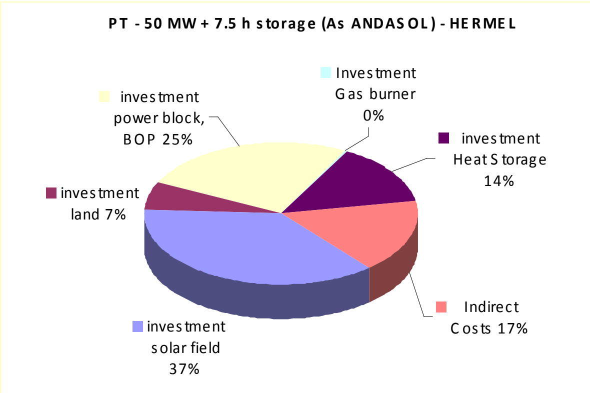


Figure 30. Components and overall plant efficiencies for the PT reference cases in the tree sites.

Table 9.: Economical results for the Parabolic Trough reference system.

		PARABOLIC TROUGH (WITH HEAT STORAGE)			PARABOLIC TROUGH (WITHOUT HEAT STORAGE)		
ECONAMICAL RESULTS	**Units**	**PT - 50 MW + 7.5 h storage (As ANDASOL) - SEVILLE**	**PT - 50 MW + 7.5 h storage (As ANDASOL) - HERMEL**	**PT - 50 MW + 7.5 h storage (As ANDASOL) - DAGGET**	**PT - 50 MW + NO storage (as SEGS) - SEVILLE**	**PT - 50 MW + NO storage (As SEGS) - HERMEL**	**PT - 50 MW + NO storage (As SEGS) - DAGGET**
fixed charge rate		8.26%	8.26%	8.26%	8.26%	8.26%	8.26%
investment solar field	€	112 076 800	112 076 800	109 824 000	73 728 000	59 136 000	59 136 000
investment power block, BOP	€	77 250 750	77 250 750	77 250 750	77 250 750	77 250 750	77 250 750
Investment Gas burner	€	720 800	720 800	720 800	720 800	720 800	720 800
investment Heat Storage	€	43 301 191	43 301 191	43 222 173	55 654	55 259	55 259
investment land	€	19 868 160	19 868 160	19 468 800	11 980 800	10 483 200	10 483 200
TOTAL Investment in Plant construction	€	253 217 701	253 217 701	250 486 523	163 736 004	147 646 009	147 646 009
Indirect Costs	€	50 643 540	50 643 540	50 097 305	32 747 201	29 529 202	29 529 202
total investment including indirect costs	€	303 861 241	303 861 241	300 583 828	196 483 205	177 175 211	177 175 211
Specific Investment	€/kWe	6 077	6 077	6 012	3 930	3 544	3 544
Annual O&M costs	€	6 357 478	5 738 913	6 489 256	4 949 278	4 155 222	4 790 971
annual financing & insurance costs	€	25 113 801	25 113 801	24 842 926	16 239 123	14 643 338	14 643 338
LEC: levelised electricity costs (solar-only)	€/kWh	0.220	0.181	0.166	0.251	0.211	0.195
LEC: levelised electricity costs (HYBRID)	€/kWh	0.194	0.160	0.147	0.220	0.186	0.172
(solar) O&M cost / kWh (already included in LEC)	euro/kWh	0.0446	0.0336	0.0345	0.0589	0.0469	0.0482
Total Cost of the Water used	€/year	218 025	260 901	287 989	128 612	135 571	151 910

The input specific costs are a reasonable estimation for the Spanish plants developed last years but we have not tried to obtain more local quotations for Lebanon and for California. Thus since we have used the same input costs for Dagget and for Hermel, the estimates for the total and for the main components investment in the two types of parabolic trough plants is almost equal from site to site. The relative investment cost distribution is shown in Figure 31.



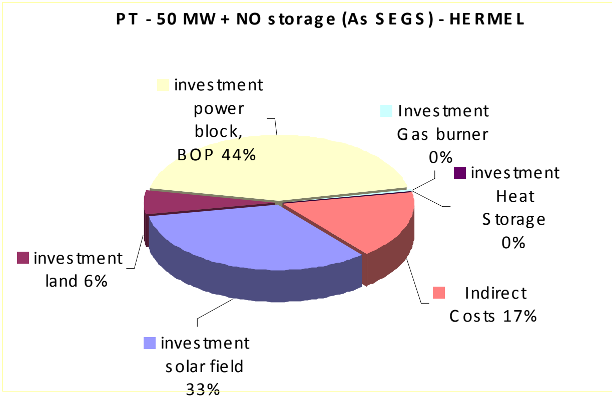


Figure 31. Relative distribution of Total Cost among Main components of a PT plant (left with 7.5 hours of heat storage; right: without heat storage).

Solar field costs represent the largest share in both cases (with and without heat storage).In the results of

Table 9 we may observe, for solar-only operation:

- Total investments of ~300 Mio.€ for the PT plant with 7.5 hours of heat storage
- The total investment in the PT plant without heat storage varies from about 200 M€ for Spain to ~180 M€ for Dagget or Hermel. The reason for this difference is that we used a larger Solar multiple for Seville (1.2) than for Dagget or Hermel (SM = 1.05).
- The Levelized Electricity Cost (LEC) for the PT plant with 7.5 hours of heat storage is lower (in each site) than for the plant without heat storage.
- LEC varies from 22 cents€/kWh (for Seville) to 18.1 cents€/kWh for Hermel and to 16.6 cents€/kWh for Dagget for the PT with storage.
- For the PT without heat storage, the LEC varies from 25 cents€/kWh (for Seville), to 21.1 cents€/kWh for Hermel and 19.5 cents€/kWh for Dagget.
- Between 3.3 and 5.5 cents€/kWh of this amount is attributed to O&M costs in the different cases.
- The specific cost of the installation is about 3500 € /kW_{el} for the the case without THS and about 6000 € /kW_{el} for the PT plant with THS. This appears to be very high compared to conventional power systems, but one must kept in mind, that this number includes “virtually” the lifetime fuel costs of the system. Therefore, this number depends strongly on the capacity factor of the plant. Designing the plant with a lower capacity factor (smaller field, smaller storage system) would reduce this figure, but LEC would increase.

2.4. Central Receiver using molten salt as heat transfer fluid with large heat storage reference system (Gemasolar typology)

To provide high annual capacity factors with solar-only power plants, a cost-effective thermal storage system must be integrated. One such thermal storage system employs molten nitrate salt as the receiver heat transfer fluid and thermal storage media. The usable operating range of molten nitrate salt, a mixture of 60% sodium nitrate and 40% potassium nitrate, matches the operating temperatures of modern Rankine cycle turbines. In a molten-salt power tower plant, cold salt at 290 °C is pumped from a tank at ground level to the receiver mounted atop a tower where it is heated by concentrated sunlight to 565°C. The salt flows back to ground level into another tank. To make electricity, hot salt is pumped from the hot tank through a steam generator to make superheated steam. The superheated steam powers a Rankine-cycle turbine. A schematic of a molten-salt power tower is shown in Figure 32. The collector field can be sized to collect more power than is demanded by the steam generator system, the excess salt accumulated in the hot storage tank. A key advantage of molten salt-based central receivers is that turbine operation is not immediately affected by clouds or high wind speeds.

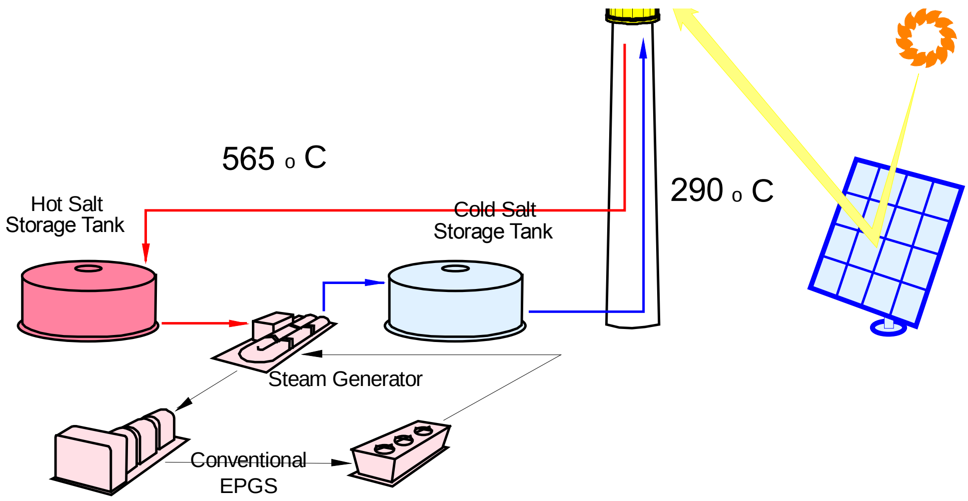


Figure 32: Process flow diagram of molten salt SCR plant [2].

Moreover, they can dramatically increase productivity by allowing CSP plant operators to store excess heat during sunny periods in molten salt storage tanks, and convert it to electricity at night. With this type of storage system, solar power tower plants can be built with annual capacity factors up to 70%. Due to the high operating temperature, up to 560ºC in the receiver outlet, each kilogram of salt can store three times more energy than in a parabolic trough plant.

The high thermal storage capacity of molten salt also results in several operational advantages, including the better management of turbine power and improved asset utilization. The lack of mobile piping systems, swivel joints and thermal oil also reduces the potential for fire or land contamination as a result of leaks and, because fluids are concentrated in a small area, they are also subject to lower levels of thermal loss and maintenance costs.

Further advantages include the fact that the same fluid can be used in the receiver and for heat storage, avoiding the need for a heat exchanger. Because molten salts reach such high temperatures they also enable operators to maximize steam-cycle thermodynamic efficiency.

Several molten salt development and demonstration experiments have been conducted over the past two and half decades in the USA and Europe to test entire systems and develop components. The largest demonstration of a molten salt power tower was the Solar Two project - a 10 MW power tower located near Barstow, CA. Recently, (in May 2011) Masdar and Sener's joint venture, Torresol Energy, has commissioned its 19.9MW commercial-scale Gemasolar concentrated solar power (CSP) plant in Seville, Spain. The CSP plant features a central tower receiver and thermal storage capabilities, which have been constructed in the Andalucía region of Spain with solar energy.

Looking ahead, prospects for the continued large-scale commercial and market development of molten salt-based central receiver technology look good. The Gemasolar technology is being promoted both by SolarReserve (inheriting the Solar Two technology) which is developing a 50 MWe + 18 hours of heat storage CR plant in Spain and several projects in US and by Masdar which is currently working on other solar power projects within the UAE including Shams One and Noor One projects, each with 100MW capacity. Besides, Torresol is already considering the implementation of a tower plant with a 50 MW turbine, or a cluster of four similar towers sharing some common elements.

Molten salt power tower technology is probably the leading contender for the future of CSP. Although molten salt-based central receivers are still much less widely used than the more common parabolic trough designs, many observers consider the technology to be the future of CSP.

The Gemasolar plant features 2650 heliostats, which reflect the light of the sun, concentrating the irradiation of 300,000 m2 of mirrors onto the reduced surface of a receiver.

Molten salts are then pumped to cool the surface 'hot-spot' down and stored at a temperature of 565ºC. Once the hot molten salt tank has reached a pre-agreed minimum level, plant operators start pumping salts to the steam generator, at the rate required, to feed a steam-turbine connected to an electrical generator. Although only equipped with a 19.9 MW turbine, the Gemasolar facility will produce more than 100 GWh/year due to the huge storage system – also enabling round-the-clock production

Torresol Energy received €171 million in financing from financial institution such as Banco Popular, Banesto ICO and the European Investment Bank in order to bring the project to fruition. Sener provided the technology and engineering detail support as well as part of the EPC and commissioning responsibility for the plant.

Sener advised that the Gemasolar CSP plant used innovate technology to power the system. In particular, the CSP plant's molten salt storage system and receiver absorbs 95% of the radiation from the sun's spectrum and delivers this energy to the molten salt compound, which moves inside the receiver and is then able to heat steam and operate the steam turbines.

The basic data for Gemasolar show few differences from one source to another. These differences are more in the nominal power of the turbine and in the size of the solar field. We attach (Figure 33) the data published in tha SolarPaces data base and several updates we consider more. Among the reasons for that is that the project design has been released several times.

Gemasolar Thermosolar Plant

This page provides information on Gemasolar Thermosolar Plant, a concentrating solar power (CSP) project, with data organized by background, participants, and power plant configuration.

Status Date:	April 17, 2009

Background

Technology:	Power tower
Status:	Under construction
Country:	Spain
City:	Fuentes de Andalucía
Region:	Andalucía (Sevilla)
Lat/Long Location:	37°33′ 44.95″ North, 5°19′ 49.39″ West
Land Area:	190 hectares
Solar Resource:	2,062 kWh/m²/yr
Source of Solar Resource:	Sener
Electricity Generation:	100,000 MWh/yr (Expected/Planned)
Contact(s):	Juan Ignacio Burgaleta
Company:	Sener
Break Ground:	February 2009
Start Production:	December 2010
Cost (approx):	230,000,000 Euro
Construction Job-Years:	800
Annual O&M Jobs:	45

Participants

Developer(s):	Torresol Energy
Owner(s) (%):	MASDAR (40%) Sener (60%)
EPC Contractor:	UTE C.T. Solar Tres
Operator(s):	Gemasolar 2006, S.A.

Plant Configuration

Solar Field

Heliostat Solar-Field Aperture Area:	318,000 m²
# of Heliostats:	2,650
Heliostat Aperture Area:	120.0 m²
Heliostat Manufacturer:	Sener
Heliostat Description:	Sheet metal stamped facet
Heliostat Drive Manufacturer:	Sener
Tower Height:	150 m
Receiver Manufacturer:	Sener
Heat-Transfer Fluid Type:	Molten salts (sodium and potassium nitrates)
Receiver Inlet Temp:	290°C
Receiver Outlet Temp:	565°C
Receiver Temp. Difference:	275°C

Power Block

Turbine Capacity (Net):	17.0 MW
Output Type:	Rankine
Cooling Method:	Wet cooling
Fossil Backup Type:	Natural gas

Thermal Storage

Storage Type:	2-tank direct
Storage Capacity:	15 hour(s)
Thermal Storage Description:	One cold-salts tank (290°C) from where salts are pumped to the tower receiver and heated up to 565°C, to be stored in one hot-salts tank (565°C)

Project Overview

Project Name:	Gemasolar Thermosolar Plant (Gemasolar)
Country:	Spain
Location:	Fuentes de Andalucía (Andalucía (Sevilla))
Owner(s):	MASDAR (40%) Sener (60%)
Technology:	Power tower
Turbine Capacity:	Net: 17.0 MW
Status:	Under construction
Start Year:	2010

Figure 33. Basic data for Gemasolar published in 2009 in: http://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=40

Table 10. Main Gemasolar data used for the analysis

Gemasolar Main Data	
Total aperture	304.750 m2
Number of Heliostats	2.650
Aperture surface of each Heliostat	115 m2
Land area	142 Ha
Thermal Power on Receiver	120 MWt
Tower heigh	140 m
Heat Storage Capacity	15 hours
Nominal Power of Turbine	19.9 MWe
Electricity production	110.000 MWh
Capacity Factor	74 %
Saving of CO2	30.000 t/year

2.5. Central Receiver using saturated water steam as heat transfer fluid with small heat storage reference system (PS20 typology).

"The PS20 Solar Power Plant (Spanish: Planta Solar 20) is a CSP plant in Sanlucar la Mayor near Seville in Andalusia, Spain, and the world's most powerful solar power tower. The 20 megawatt (MW) solar power tower produces electricity with large movable mirrors called heliostats.

"Construction was started in 2006; PS20 was put into operation in 2009

(Figure 20). It features a number of significant technological **improvements over the earlier PS10.** These include a higher-efficiency receiver, various improvements in the control and operational systems, and a better thermal energy storage system.

PS10 (Figure 20) is solar concentration solar thermal tower plant working with direct saturated steam generation (DSG) concept, at considerably low values of temperature and pressure (250ºC @ 40bar). Some other design criteria taken into consideration for PS10 solar plant basic configuration has been related to solar multiple value and heat storage capacity for plant operation during no solar periods (Figure 34).

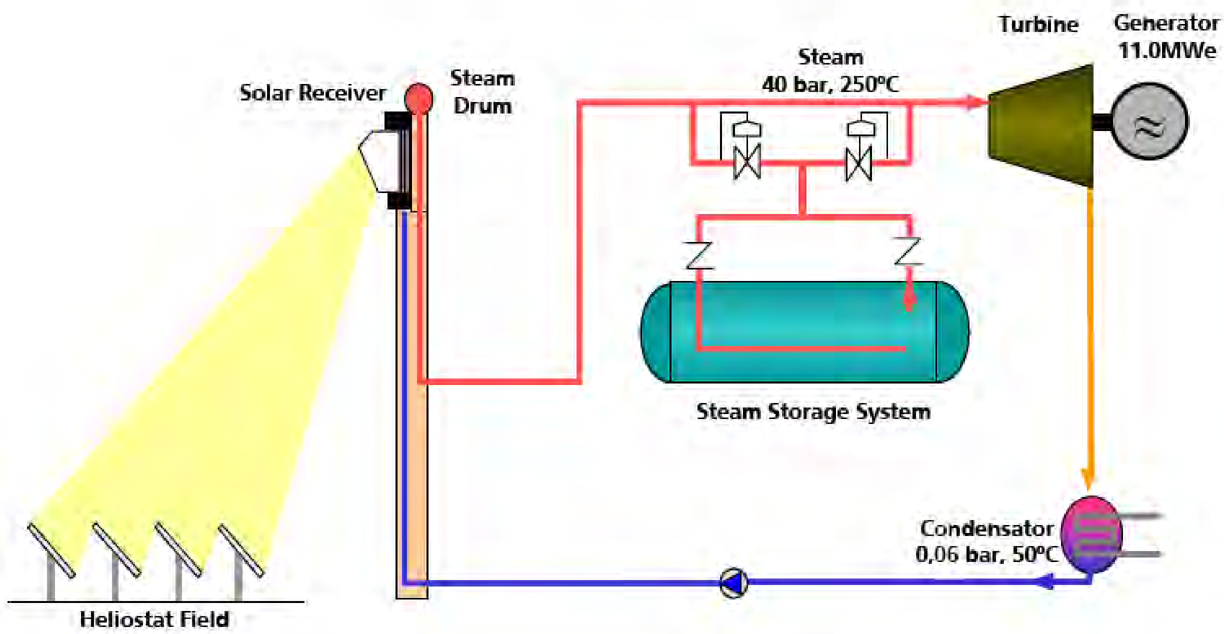


Figure 34. Scheeme of PS10 and PS20 CR plants.

Spanish regulations don't allow hybridization of CSP plants out of the limits of 15% of annual generated electricity from fossil fuels. In this sense one of the key factors for a CST plant design is related to the decision of considering dailies shut-downs and start-ups of the steam turbine, or in the other hand, to consider huge storage capacity to cover at least in several months in the year (summer time) night periods in operation running the turbine from storage, reducing so the number of stoppages and cools of the turbine.

Keeping the general idea for not considering additional risky subsystems in its first commercial plant Solúcar decided to propose a small storage concept for PS10, assuming that starting and stopping the saturated steam turbine under controlled temperature conditions is a feasible operational procedure. Is for that than PS10 has been designed under a small **solar multiple** value, (**1.3**).

This design allows the plant to dispose of the availability of a small stored energy capacity to deal with some short cloudy transient periods in order to protect the turbine and associated systems from overcame lacks of solar power that could damage equipments.

PS10 heliostat field is composed by 624 heliostats for a total reflective surface of 75.216m2. It is arranged in 35 circular rows around the tower. Each heliostat, Sanlúcar 120 type, is a mobile 121 m2 curved reflective surface mirror that concentrates solar radiation on a receiver placed on top of a 100 m tower. For this purpose, every heliostat is spherically curved so its focal point is at a distance equal to the slant range to the receiver.

The Sanlúcar 120 heliostat is composed by 28 (7rows and 4 columns) curved facets manufactured with high reflectance mirror in order to provide the required optical properties to the heliostat field. Heliostat field has been designed using the latest calculation procedures and simulation tools with the objective of minimizing losses by cosine, shadowing, blocking, air transmittance and spillage effects. In this sense annual mean cosine effect in PS10 plant is over 81% and losses because shadows and blocks are not higher than 4.5% in annual basis.

The high accuracy 2 axis sun tracking that is required for projecting sun disk image onto the receiver is provided by a mechanical drive guided by a local control system.

At the top of the tower is placed the receiver. The receiver is the system where concentrated solar radiation energy is transferred to the working fluid to increase enthalpy. PS10 receiver is based on cavity concept to reduce as much as possible radiation and convection losses. The receiver is basically a forced circulation radiant boiler with low ratio of steam at the panels output, in order to ensure wet inner walls in the tubes. Special steel alloys have been used for its construction in order to operate under important heat fluxes and possible high temperatures. It has been designed to produce above 100.000 kg/h of saturated steam at 40bar- 250ºC from thermal energy supplied by concentrated solar radiation flux.

It is formed by 4 vertical panels 5,40m width x 12,00m height each one to conform an overall heat exchange surface of about 260m2. These panels are arranged into a semi-cylinder of 7,00m of radius. During operation at full load, absorber panels will receive about 55,0MWt of concentrated solar radiation with **peaks of 650kW/m2**.

Steam produced in the receiver is sent to the turbine where it expands to produce mechanical work and electricity. PS10 turbine operates at 250ºC and 40bar saturated steam conditions. At the exit of the turbo generator unit steam is sent to a low pressure water-cooled condenser.

Condenser exit is preheated with turbine extractions at low and medium pressures. Output of first pre-heater is sent to a deaerator, fed with steam from another turbine extraction. A third and last pre-heater is fed with steam from receiver. It increases water temperature till 245ºC. When mixed with returned water from drum, a 247ºC under cooled input feed to the receiver is obtained.

For cloudy transient periods, the plant has a saturated water thermal storage system with a thermal capacity of 20 MWh, equivalent to an effective operational capacity of 50 minutes at 50% turbine workload. The system is composed by 4 tanks that are sequentially operated in relation to their charge status. During full load operation of the plant, part of steam produced by receiver at 250ºC-40bar will be employed to load the thermal storage system. When energy is needed to cover a transient period, energy from saturated water will be recovered at variable pressure, from 40bar to minimum pressure allowed by the system to run the turbine at a 50% partial load.

The four Thermal storage tanks for PS10

«**PS20** uses the same technology (but double in size) as PS10 and consists of a solar field made up of 1,255 mirrored heliostats designed by Abengoa Solar. Each heliostat, with a surface area of 120 m^2 (the same as in PS10), reflects the solar radiation it receives onto the receiver, located on the top of a 165 m high tower, producing steam which is converted into electricity generation by a turbine.”

Planta Solar 20

This page provides information on Planta Solar 20, a concentrating solar power (CSP) project, with data organized by background, participants, and power plant configuration. Abengoa Solar's Planta Solar 20 (PS20) is a 20-megawatt power tower plant being constructed next to the PS10 tower, and it will be the largest power tower in the world. The PS20 receiver has been significantly improved with respect to its predecessor PS10 receiver. For example, designing a natural circulation receiver and increasing incident solar radiation capture will increase net electrical power output by 10 percent. The 160-meter tower was designed to reduce the visual impact of its height. The plant has the capacity to generate more than 40 gigawatt-hours of energy each year, enough to supply power to 10,000 homes.

Status Date:	April 21, 2009

Background

Technology:	Power tower
Status:	Operational
Country:	Spain
City:	Sevilla
Region:	Sanlúcar la Mayor
Lat/Long Location:	37°26' 30.97" North, 6°14' 59.98" West
Land Area:	80 hectares
Solar Resource:	2,012 kWh/m^2/yr
Source of Solar Resource:	Abengoa Solar
Electricity Generation:	48,000 MWh/yr (Expected/Planned)
Generation Data Explanation:	Gross generation
Contact(s):	Ana Cabañas
Company:	Abengoa Solar
Key References:	Web site
Break Ground:	2006
Start Production:	April 22, 2009
PPA/Tariff Date:	January 17, 2005
PPA/Tariff Type:	Royal Decree 661/2007
PPA/Tariff Rate:	27.1188 Euro cents per kWh
PPA/Tariff Period:	25 years
PPA/Tariff Information:	Total Price = Pool + Tariff Rate
Project Type:	Commercial plant
Incentives:	1.9 million Euros from Andalusian Regional Government
Developer(s):	Abengoa Solar
Owner(s) (%):	Abengoa Solar
EPC Contractor:	Abener Energía
Operator(s):	Abengoa Solar
Generation Offtaker(s):	Electric Market (Pool) Endesa Distribución (FIT)

Plant Configuration

Solar Field

Heliostat Solar-Field Aperture Area:	150,000 m²
# of Heliostats:	1,255
Heliostat Aperture Area:	120.0 m²
Heliostat Manufacturer (Model):	Abengoa (Solucar 120)
Heliostat Description:	Glass-metal
Tower Height:	165 m
Receiver Type:	Cavity
Heat-Transfer Fluid Type:	Water
Receiver Outlet Temp:	250 - 300°C

Power Block

Turbine Capacity (Gross):	20.0 MW
Turbine Capacity (Net):	20.0 MW
Output Type:	Rankine
Power Cycle Pressure:	45.0 bar
Cooling Method:	Wet cooling
Cooling Method Description:	Refrigeration towers
Fossil Backup Type:	Natural gas
Backup Percentage:	0%

Project Overview

Project Name:	Planta Solar 20 (PS20)
Country:	Spain
Location:	Sevilla (Sanlúcar la Mayor)
Owner(s):	Abengoa Solar
Technology:	Power tower
Turbine Capacity:	Net: 20.0 MW Gross: 20.0 MW
Status:	Operational
Start Year:	2009

Do you have more information, corrections, or comments?

Figure 35. Basic data for PS20. (http://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=39)

2.5.1. Cost and performance of both Central Receiver Reference Systems

The two Central Receiver plants have different configurations of the solar field: a surrounding solar field in case of Gemasolar Typology and a North field in case of PS20 typology. For this assessment which implies hourly simulation of the plant performance, both solar fields were pre-designed using a separate design tool (termed WinDELSOL) which provides a solar field optical performance matrix (optical efficiency as function of the solar altitude and azimuth). Interpolating within this matrix we may obtain the solar field efficiency for all the hours of the annual time series.

As in the case of Parabolic trough, Further optimization in a more detailed model may result in slightly different configuration or cost figures. However, the degree of detail of the used model appears sufficient to analyze the overall impact of changes in cost and performance.

The input parameters for the pre-designed PS reference plants may be found in the next (

Table 11) and (Table 12).

Table 11: Technical Input parameters for Central Receiver Reference Systems.

Technical Input Parameters	Units	CR - 20 MW + 15 h storage (As GEMASOLAR) - HERMEL	CR - 20 MW + 0.5 h storage (As PS-20) - HERMEL
Solar Field			
Site		Hermel	Hermel
Longitud		36.39	36.39
Latitude	°	34.39	34.39
Time zone	-	3	3
Solar Multiple		**3**	**1.3**
Direct Normal Irradiation		**2445**	**2445**
Total Aperture Surface	**m2**	**304 520**	**150 600**
Aperture surface for Solara Multiple = 1	m2	101507	115846
Required Ground Surface	km2	1.5226	0.753
Aperture Surface per Heliostat	**m2**	**115**	**120**
Total Number of Heliostats		**2648**	**1255**
Annual Mean Reflectivity of the mirrors	-	0.88	0.88
Optical Peak Efficiency (design point)		0.75	0.75
HTF temperature at field exit	**°C**	**565**	**250**
Mean Cocentarted solar Flux on Receiver aperture (design point)	**kW/m2**	**500**	**350**
Absortivity of solar receiver	%one	0.93	0.93
Mean Design Optical field efficiency		0.5725	0.57
Heat Transfer			
Incident Thermal Power on receiver	**kW**	**148187**	**72966**
design parasitics for pumping and tracking (total)	kW	**1979**	**241**
Factor for power block parasitics		3.00%	3.00%
threshold angle for sunrise/sunset	° (grados)	7	7
Design Net Electrical Output	**kW**	**19000**	**20000**
Design Efficiency of the Power Block (nominal conds.)	**-**	**0.39**	**0.295**
Overall plant availability	-	0.98	0.98
Storage Capacity (nominal hours)	**h**	**15.0**	**0.5**
Thermal Capacity of the Storage	kWh	806899	34307
Storage efficiency		0.98	0.95
HTF temperature in storage discharging	**°C**	**560**	**240**
Overall plant availability		**0.96**	**0.98**

It may be observed (see Table 11):

- The reference plants were designed: 1) with a 3 times larger solar field than needed to provide the design power (solar multiple = 3) and about 15 hours storage in the case of a rather dispatch able plant, like Gemasolar type; and 2) with a 1.3 times larger solar field than needed to provide the design power (solar multiple = 1.3) for the case of PS20 type (plant with a reduced heat storage).

- As shown in Table 6 both plants have quite different solar field aperture for similar nominal power (~20 MWe): abut 300.000 m2 in case of plant with 15 of heat storage and, about 150.000 m2 (for the Hermel used DNI) for the case of PS20 without 0.5 h heat storage.

Table 12: Cost Input parameters for Central Receiver Reference Systems

O&M Input	Units	CR - 20 MW + 15 h storage (As GEMASOLAR) - HERMEL	CR - 20 MW + 0.5 h storage (As PS-20) - HERMEL
Labour costs per employee	€/a	48000	48000
number of persons (without field maintenance)		20	20
number of persons for field maintenance		**15.2**	**4.5**
Water costs per MWh electricity produced	€/MWh	1.3	1.3
O&M Equipment costs percentage of investment	%	1.00%	1.00%
Specific Fix O$M cost associated to the Power Block	Euro/ kWe	27	27
Specific Variable O$M cost associated to the Power Block	Euro/ MWh	2.5	2.5
Cost input			
Specific investment cost for solar field	€/m2	**186.0**	**186.0**
Specific investment cost for power block	€/kW_e	**1600.0**	**1650.0**
Specific Investment Cost for Heat Storage	€/kWh_th	**29.0**	**65.0**
Spaecific Cost for civil works	€/m2	4	4
Investment in Tower	€	5 178 911	4 197 894
Auxialiary Gas Burner cost	€/kWth	42	42
Specific Investment for Receiver	€/kWh_th	230.0	85.0
annual **Insurance** cost		1.0%	1.0%
Life time	years	30	30
dept interest rate (kd)		**6.00%**	**6.00%**
surcharge for construction	%	10%	10%
surcharge for engineering & management	%	5%	5%
surcharge for contingencias	%	5%	5%
Fuel cost for hybridization	€/MWh	15	15
Mean price of conventinal electricity	€/MWh	40	40

The labour costs per employee have been assumed different for Lebanon (30.000 €/year) that for Spain and California (48.000 €/year).

The Financial parameter affect very much to the cost of electricity produced. To focus the assessment on the optional technologies, we have assumed reasonable (at least for Spain), and equal for all the technologies, financial parameters.

The cost Inputs for equipment are approximated and coincident with the figures used in the Spanish projects.

Using the modelling in hourly base we have found the technical and economical results that are shown in the next tables.

Table 13. Technical Results for CR reference systems

		Central Receiver WITH 15H HEAT STORAGE			Central Receiver ~WITHOUT HEAT STORAGE		
Technical RESULTS	**Units**	**CR - 20 MW + 15 h storage (As GEMASOLAR) - SEVILLE**	**CR - 20 MW + 15 h storage (As GEMASOLAR) - HERMEL**	**CR - 20 MW + 15 h storage (As GEMASOLAR) - DAGGET**	**CR - 20 MW + 0.5 h storage (As PS-20) - SEVILLE**	**CR - 20 MW + 0.5 h storage (As PS-20) - HERMEL**	**CR - 20 MW + 0.5 h storage (As PS-20) - DAGGET**
annual Net electricity output (solar only)	**MWh**	**88 804**	**105 266**	**121 089**	**40 721**	**47 284**	**54 564**
Annual (solar-only) Gross Electricity produced	MWh	93 785	111 215	127 951	42 279	49 119	56 746
NET Electricity Production using 15% ohybridization with Gas	MWh	104 475	123 842	142 458	47 907	55 629	64 193
Gross Electricity Production using 15% hybridization with Gas	MWh	106 574	126 381	145 398	49 739	57 788	66 760
Parasitics	MWh	5860	6981	8047	1701	1985	2297
TOTAL DNI incident on Aperture	%	613 645	744 624	850 044	303 442	368 253	420 388
Anual efficiency Solar Field (combined with Receiver in case PT)		53.43%	51.76%	52.31%	61.19%	59.33%	60.61%
Annual Mean Efficiency of Receiver	**%**	**77.88%**	**79.26%**	**79.34%**	**90.54%**	**90.91%**	**90.95%**
Annual Mean efficiency Power Block	%	38.35%	38.40%	38.43%	26.35%	26.65%	26.50%
Annual Gross Effiency of the Plant	**%**	**15.96%**	**15.76%**	**15.95%**	**14.60%**	**14.37%**	**14.61%**
Loss of Efficiency due to Parasitics (% of the total eff.)	%	6.60%	6.63%	6.65%	4.18%	4.20%	4.21%
(A1dumping) /(used thermal power)	%	0.65%	1.62%	2.07%	2.24%	5.19%	5.73%
Annual NET Efficiency	**%**	**14.91%**	**14.71%**	**14.89%**	**13.99%**	**13.77%**	**14.00%**
Annual Mean Incident Solar Flux on Receiver	kW/ m2	346	390	393	244	296	301
Total Energy passing in Heat Storage	MWh	1 254 509	1 755 759	2 140 588	24 008	36 621	46 945
Mean Heat Storage Efficiency	%	99.83%	99.84%	99.85%	98.81%	99.04%	99.01%
Annual CAPACITY FACTOR	**%**	**62.77**	**74.41**	**85.59**	**27.34**	**31.75**	**36.64**

In the results of Table 13 we may observe (**for solar-only operation**):

- Annual electricity productions, for **CR with 15h heat storage**, of 88.8 GWh (for DNI as in Seville), 105.3 GWh (for DNI as the used for Hermel) and about 121.1 GWh (for Dagget)..
- In case of the CR with only 0.5 hours of THS, the annual electricity productions are less than half respect to the previous case.
- Annual Capacity Factors, varies within 27-36% for the plants with only 0.5 h heat storage and are estimated from 63% to 85% for the CR plant with 15 hours of heat storage in the different sites.
- The Gross overall efficiency of the plants are very similar from site to site (this is mainly due

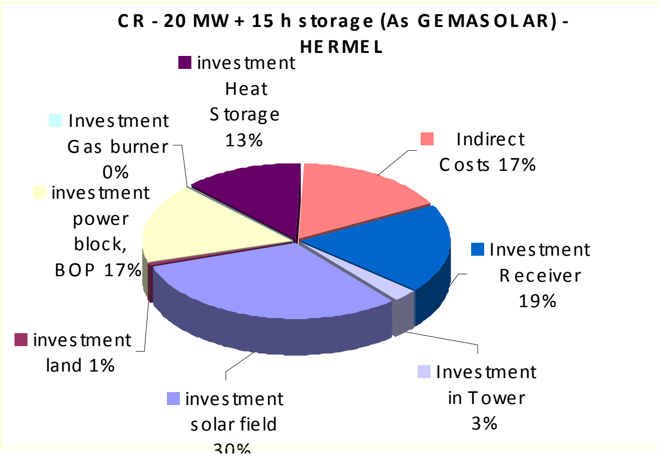
to the fact that the three sites have similar latitudes) varying between 15.8% to 16.0% for Gemasolar type and varying within 14.4%-14.6% for the PS20 type.

- The NET overall annual efficiencies estimates are about 1% better than for the PT reference cases, and in the order of 14% for the PS20 type and 15% for Gemasolar type.
-

Table 14.: Economical results for the Central Receive reference systems.

ECONAMICAL RESULTS	Units	CR - 20 MW + 15 h storage (As GEMASOLAR) - SEVILLE	CR - 20 MW + 15 h storage (As GEMASOLAR) - HERMEL	CR - 20 MW + 15 h storage (As GEMASOLAR) - DAGGET	CR - 20 MW + 0.5 h storage (As PS-20) - SEVILLE	CR - 20 MW + 0.5 h storage (As PS-20) - HERMEL	CR - 20 MW + 0.5 h storage (As PS-20) - DAGGET
fixed charge rate		**8.26%**	**8.26%**	**8.26%**	**8.26%**	**8.26%**	**8.26%**
investment solar field	€	56 640 720	56 640 720	56 640 720	28 011 600	28 011 600	28 011 600
investment power block, BOP	€	30 400 000	30 400 000	30 400 000	33 000 000	33 000 000	33 000 000
Investment Receiver	€	34 083 020	34 083 020	34 083 020	6 202 085	6 202 085	6 202 085
Investment in Tower	€	5 178 911	5 178 911	5 178 911	4 197 894	4 197 894	4 197 894
Investment Gas burner	€	720 800	720 800	720 800	840 000	840 000	840 000
investment Heat Storage	€	23 400 078	23 400 078	23 400 078	2 229 936	2 229 936	2 229 936
investment land	€	1 218 080	1 218 080	1 218 080	602 400	602 400	602 400
TOTAL Investment in Plant construction	**€**	**151 641 609**	**151 641 609**	**151 641 609**	**75 083 915**	**75 083 915**	**75 083 915**
Indirect Costs	€	30 328 322	30 328 322	30 328 322	15 016 783	15 016 783	15 016 783
total investment including indirect costs	**€**	**181 969 931**	**181 969 931**	**181 969 931**	**90 100 698**	**90 100 698**	**90 100 698**
Specific Investment	€/ kW_el	9 577	9 577	9 577	4 505	4 505	4 505
Annual O&M costs	€	4 057 719	4 120 274	4 180 403	2 622 443	2 647 384	2 675 047
annual financing & insurance costs	€	15 039 617	15 039 617	15 039 617	7 446 725	7 446 725	7 446 725
LEC: levelised electricity costs (solar-only)	**€/ kWh_ el**	**0.2176**	**0.1842**	**0.1607**	**0.2473**	**0.2135**	**0.1855**
LEC: levelised electricity costs (HYBRID)		**0.1910**	**0.1626**	**0.1426**	**0.2162**	**0.1875**	**0.1637**
(solar) O&M cost / kWh (already included)	euro/ kWh	**0.0457**	**0.0391**	**0.0345**	**0.0620**	**0.0539**	**0.0471**
Total Cost of the Water used	€/year	135 818	160 995	185 195	62 279	72 317	83 451
Environmental Parameters							
Rate of CO2 emissions of conventional plant	kg/ kWh_e	0.500	0.500	0.500	0.500	0.500	0.500
Rate of water required for mirror washing	Liters/ kWh_e	0.300	0.300	0.300	0.300	0.300	0.300
Rate of Water required for thermodynamic cycle (lietrs/kWh)	Liters/ kWh_e	5.000	5.000	5.000	5.000	5.000	5.000
Annual CO2 Mitigation	Tons/ year	**44 402**	**52 633**	**60 545**	**20 361**	**23 642**	**27 282**
Annual Water Required	m3/ year	**613 732**	**710 567**	**803 645**	**284 715**	**323 324**	**366 145**

As already mentioned for the PT reference plants, the input specific costs are a reasonable estimation for the Spanish plants developed last years but we have not tried to obtain more local quotations for Lebanon and for California. Thus since we have used the same input costs for Dagget and for Hermel, the estimates for the total and for the main components investment in the two types of central receiver plants is almost equal from site to site. The relative investment cost distribution is shown in Figure 36.



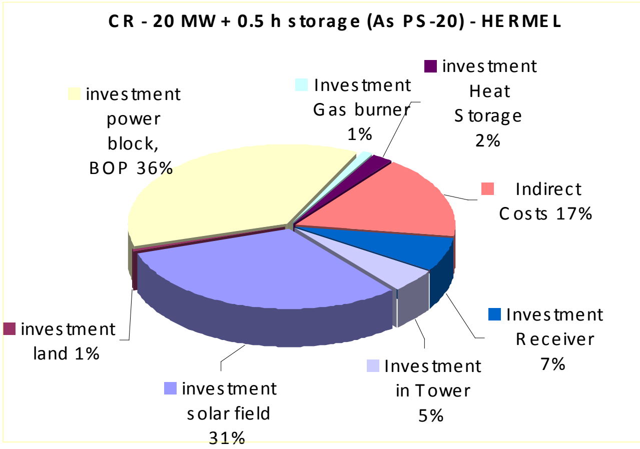


Figure 36. Relative distribution of Total Cost among Main components of a CR plant (left with 15 hours of heat storage; right: with 0.5 h heat storage).

In the results of

Table 14 we may observe, for solar-only operation:

- At a first glance the previous figures reveal the strong influence of the cheap “molten salt storage” technology on the whole cost breakdown.
- For the 19 We CR plant with 15 hours of heat storage the total investments of ~180 Mi € is double of the 20MWe CR PS20 plant whose total investment is about 90 M€.
- Since total annual electricity produced in Gemasolar (with 88.8 GWh/y –solar only- in Seville placement) is more than double than in PS20 (with 40.7 GWh/y –solar only, in Seville) this explains why the 15% of lower LEC of Gemasolar than PS20.
- The LEC estimates for Gemasolar type reference system is almost the same than for the PT Andasol type, but with 35% lower investment.
- The specific cost of the installation is about 4500 € /kW_{el} for the case without THS and about 9500 € /kW_{el} for the CR plant with 15 h THS. This number depends strongly on the capacity factor of the plant (up to ~63-85% in case of Gemasolar type). Designing the plant with a lower capacity factor (smaller field, smaller storage system) would reduce this figure, but LEC would increase.

The circular field used for the Gemasolar design is leading also to smaller towers (~140 m height) that represent only 3% of the investment than in case of PS20 with a North field and a tower of about 160 m height.

2.6. SUMMARY OF COMPARATIVE RESULTS FOR OTHER LOCALITIES

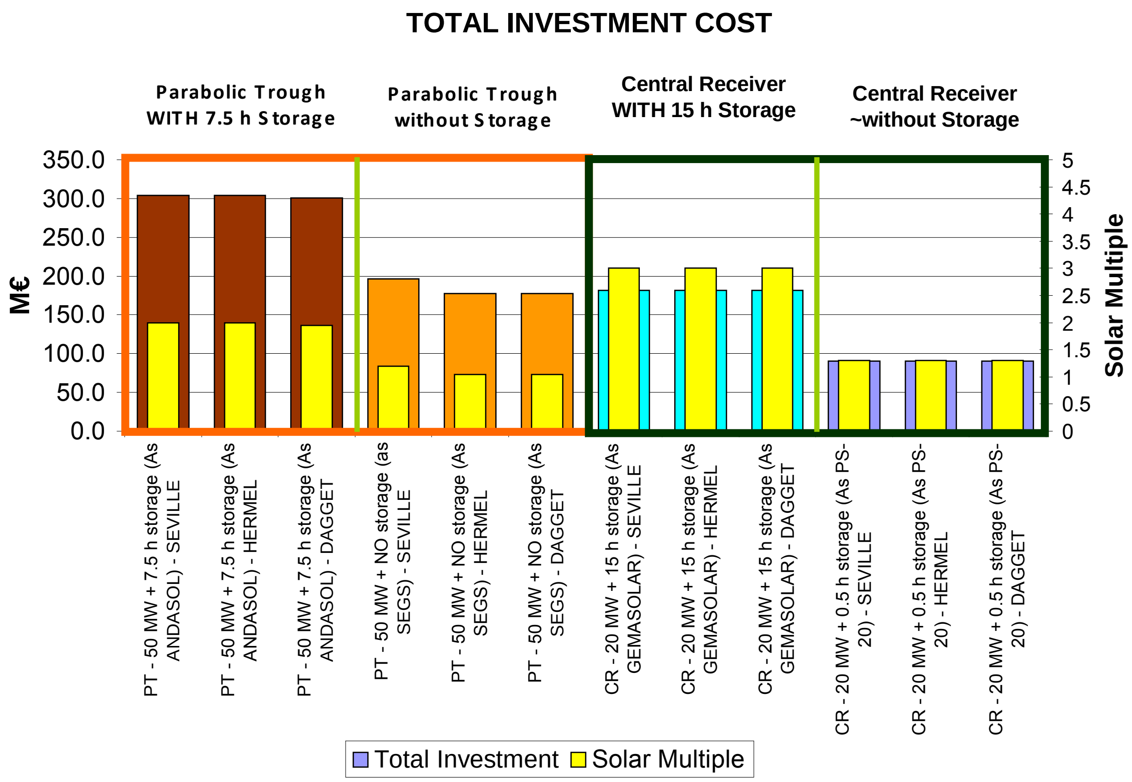


Figure 37. Relationship between total investment cost, technology type and Solar Multiple.

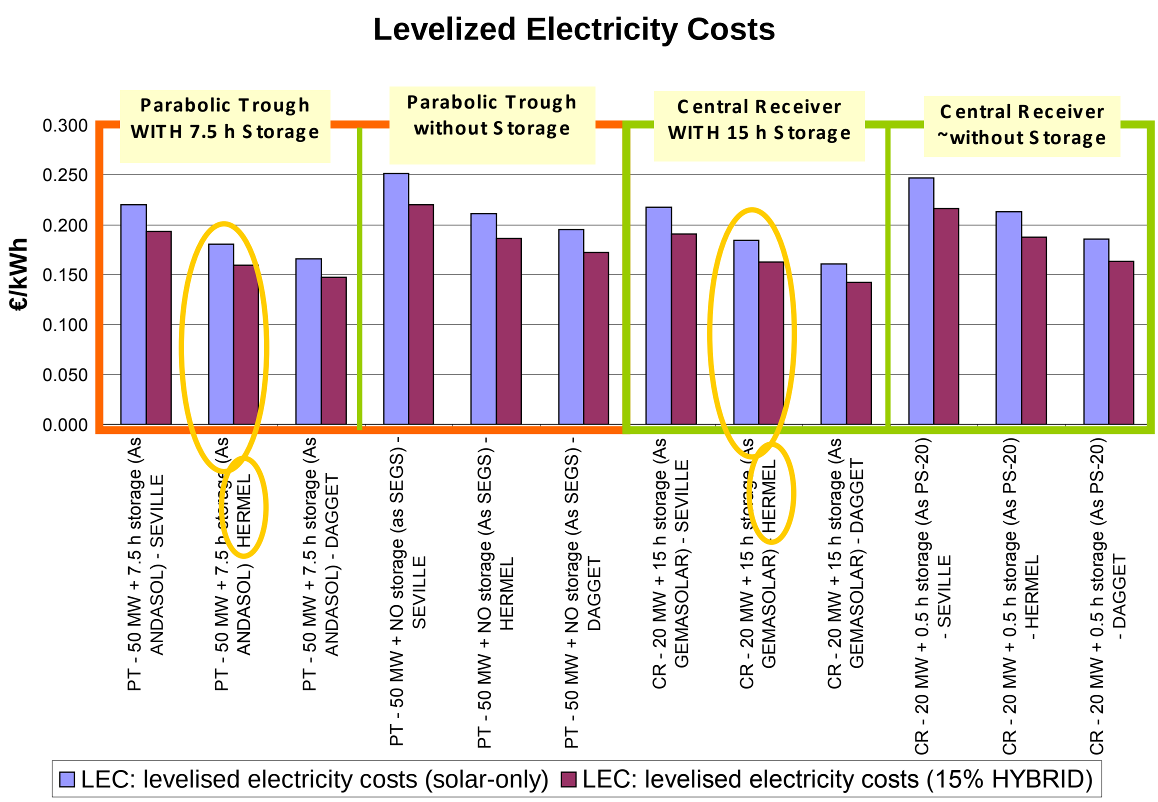


Figure 38. Levelized electricity costs for the twelve cases analysed.

It can be observed (Figure 38) that the lower electricity costs for Hermel would be in the order of 18 cents of euro per kWh of electricity.

The recommended schemes for Lebanon would be with the use of significant thermal heat storage, due to their lower levelized costs of electricity and high capacity factors. Within these schemes, no clear advantage of any of the technological options (parabolic through versus central receiver) may be stated.

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APPENDIX : Technical Note: Considerations to define a Meteorological Station for Assessment of Solar Resource and CSP sitting.

The installation of meteorological station(s) for a CSP project development should follow to a phase of pre-selection of the potential site(s) for the plant placement and should help to “validate” the previous assessment of the solar resource as main magnitude but also to collect time series of Solar Resource and of other meteorological variables that affect the plant performance as Wind, Humidity, Temperature, frequency and duration of cloud transients, etc.

Being the solar resource, in terms of its Direct Normal Irradiation component, the first selection criteria for CSP sitting, project developers need to have reliable DNI data available at specific locations, including historic trends with seasonal, daily, hourly, and (preferably) sub-hourly variability to predict the daily and annual performance of a proposed CSP plant. Without these data, no financial analysis is possible.

The data provided by the meteorological station usually will cover only one to two years before the plant construction and connection to the grid which is not enough to guaranty the “typical” resource of the site. However these data are very useful for:

Characterize of local phenomena (as typical clouds transients duration, atmospheric transmittance, wind speed and duration, temperatures and relative humidity, etc.)

To “validate” the information compiled from other sources (in terms of several statistical comparison, as total annual, monthly and daily means, and variances, etc.)

To feed the plant performance prediction models with real data, etc.

On the other hand the installation of a meteorological station in the chosen site for a CSP plant implies to foresee a maintenance and data processing which has to be taken into account during the selection of instrumentation and data recording equipment.

In this technical note we quickly survey the general requirements for the site pre-selection and we will try to provide enough information to select the appropriate instrumentation for a meteorological station.

3.1. Site Qualification

Before a CSP project is undertaken a pre-feasibility study should identify adequate zones and sites by compiling the best possible information about the quality and reliability of the solar resource but also of the other magnitudes which affect the feasibility of a CSP plant. To be feasible and cost effective, CSP plants also require relatively large tracts of nearly level open land along with other sitting characteristics. Thus, the primary criteria used for site selection includes:

- High solar resource (annual Direct Normal Insolation > 1800 kWh/m/y)
- Adequate soils and Minimal slope (< 2-4%)
- Proximity to electric grid
- Proximity to transportation corridors
- Water availability

- o Previously disturbed land
- o Adequate Meteorological conditions

To find optimal sites with high economic potential, the availability of technology potential maps would be very useful. In those maps the above criteria may be introduced (using for instance a Geographic Information System, GIS) by exclusion layers (from solar resource maps to regions where terrain would inhibit the cost-effective deployment of large-scale plants, etc.).

3.2. SOLAR IRRADIATION

There are three types or components of solar irradiation:

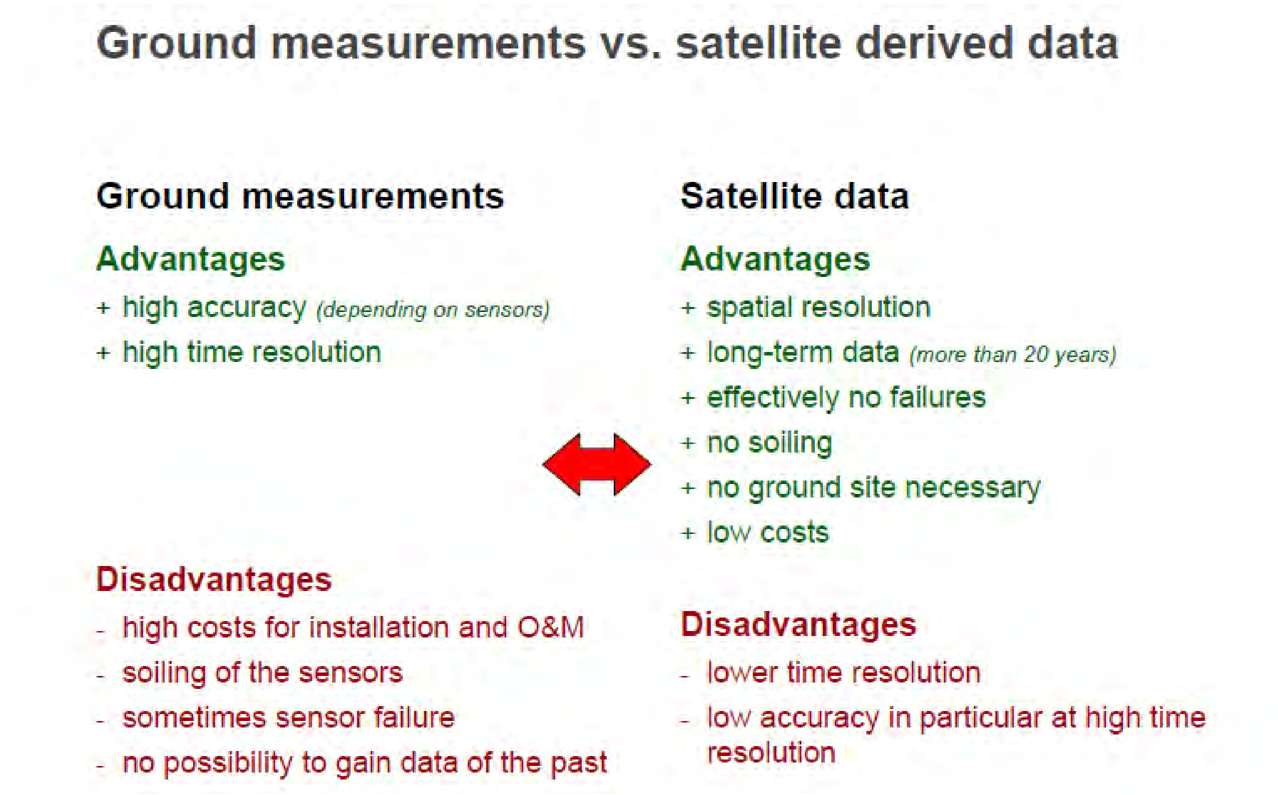
- DNI (Direct-Normal Irradiation): is the beam radiation which comes from the sun and passes through the planet's atmosphere without deviation and refraction. It is also referred as beam radiation. It is measured through pyrehiliometer.
- Diffuse solar irradiation: It is the solar radiation scattered by aerosols, dust and molecules. It does not have a unique direction and also dose not follows the fundamental principals of optics. It is measured by shading pyranometer.
- Global solar irradiation: The global solar radiation is the sum of the direct and diffuse solar radiation and is sometimes referred to as the global radiation. The most common measurements of solar radiation are total radiation on a horizontal surface often referred to as ‘global radiation’ on the surface. It is measured by pyranometer

Adequate placements for CSP plants require large or, at least, sufficient Direct Normal Ir

radiation (DNI) (Let’s say, annual DNI values larger than 1800-2000 kWh/m2/day). Sites with excellent solar radiation offer more attractive Levelised electricity prices.

What kind of DNI data is needed?. The required information to assess the potential for a CSP plant is a significant record (of about 15 years) of DNI.

However, these records are usually not available so that the application of models is usually required to fill the information gaps. These models allow estimating the DNI either from ground measurements of other solar irradiation measurements, as the GHI and the DHI observations, or from satellite data. Recently, an extended way to assess the “typical” annual DNI of a site is to apply physical and statistical models to translate the Satellite observations into DNI estimations.

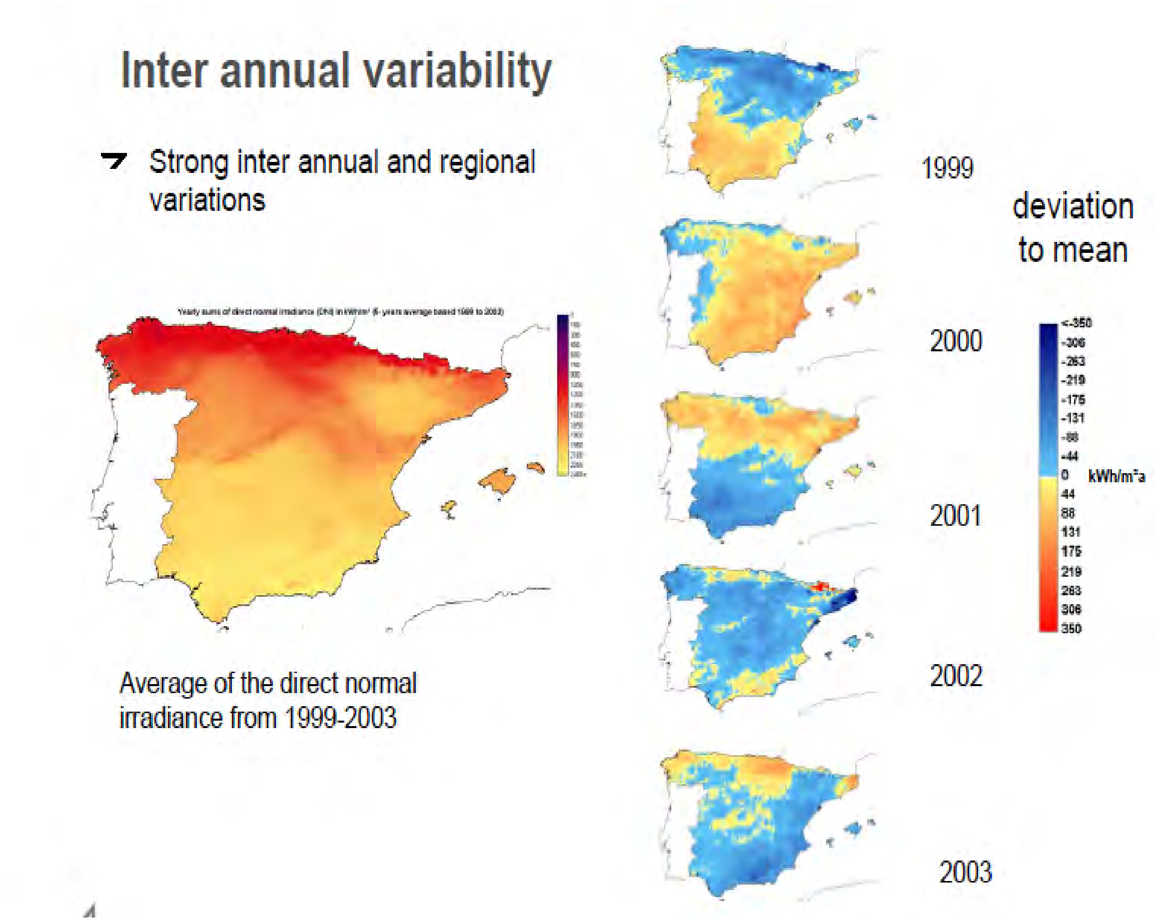


(Source R.Pitz-Paal; DLR)

Satellite derived solar radiation maps are useful in the pre-feasibility and macro-economic studies and enable the first answers to the two main sources of variability of the annual DNI:

- inter annual variability and long-term drifts (with totals amounts varying up to 10-15% from year to year)
- spatial variability (with a clear dependency on the latitude and local phenomena that affect the atmospheric transmissivity)

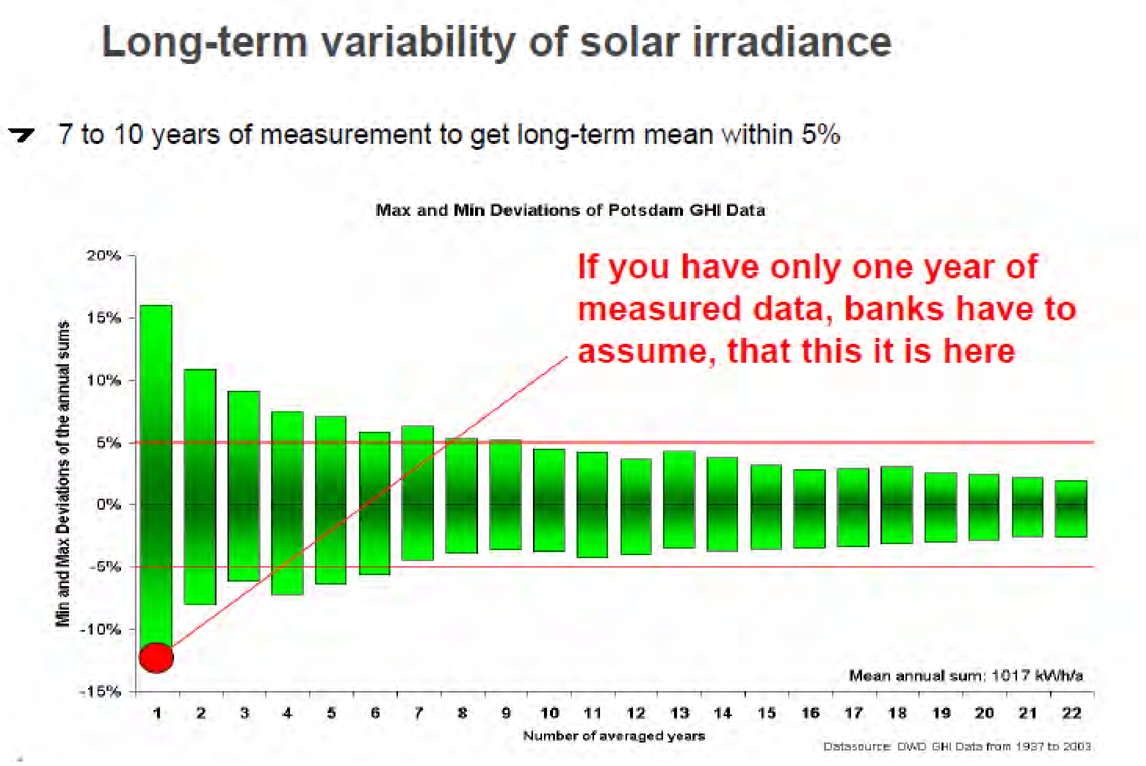
3.2.1. Inter annual variability and long-term drifts



(Source R.Pitz-Paal; DLR)

Totals amounts of DNI may vary up to 10-15% from year to year, so that energy predictions should take into account this uncertainty.

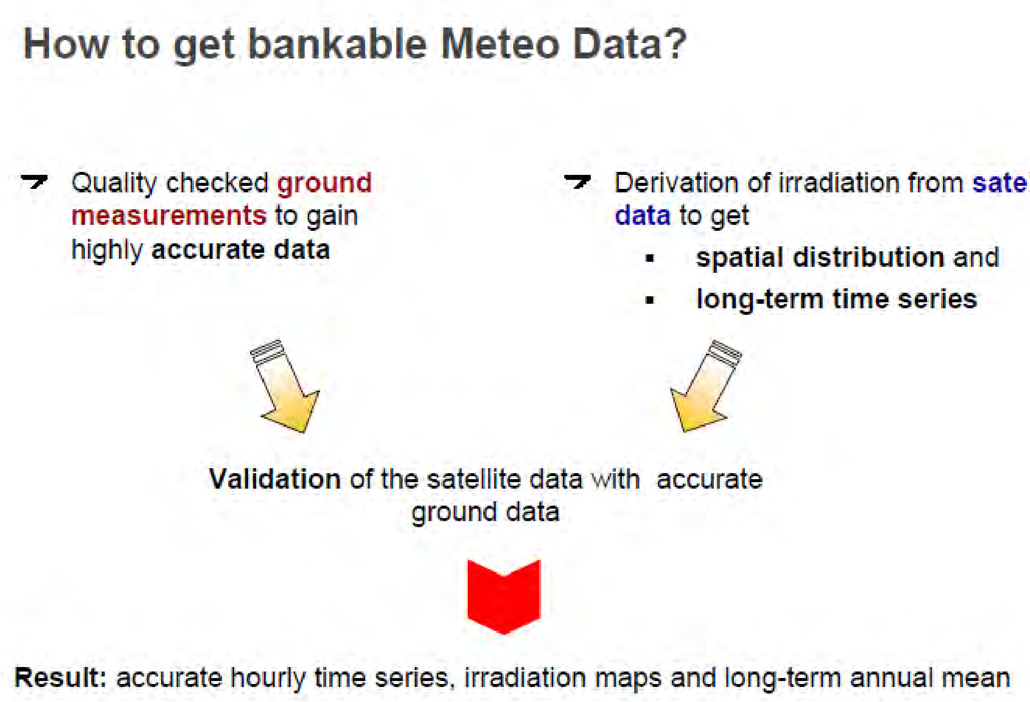
To reduce this uncertainty, as large as possible annual DNI records should be compiled. One of the proposed ways is to use the relatively large satellite data base (of about 15-20 years) to “estimate” the “typical” annual DNI for a site.



(Source R.Pitz-Paal; DLR)

Since the satellite estimations for DNI are quite indirect, the correlation with ground measurements allows increasing the reliability of the satellite estimations.

Thus, before a CSP project is undertaken, the best possible information about the quality and reliability of the DNI must be made available. That is, project developers need to have reliable data about the solar resource available at specific locations, including historic trends with seasonal, daily, hourly, and (preferably) sub-hourly variability to predict the daily and annual performance of a proposed CSP plant. Without these data, no financial analysis is possible.



3.2.2. Spatial variability

For the selection of potential placements for CSP plants DNI solar resource maps would be very helpful. However, only some approximations to DNI maps may be found derived from satellite images. Several companies (as SOLEMI, IRSOLAV, Satel-Light and NREL) offer a Geographic Information System (GIS) analysis of the large regions to identify candidate areas for concentrating solar power.

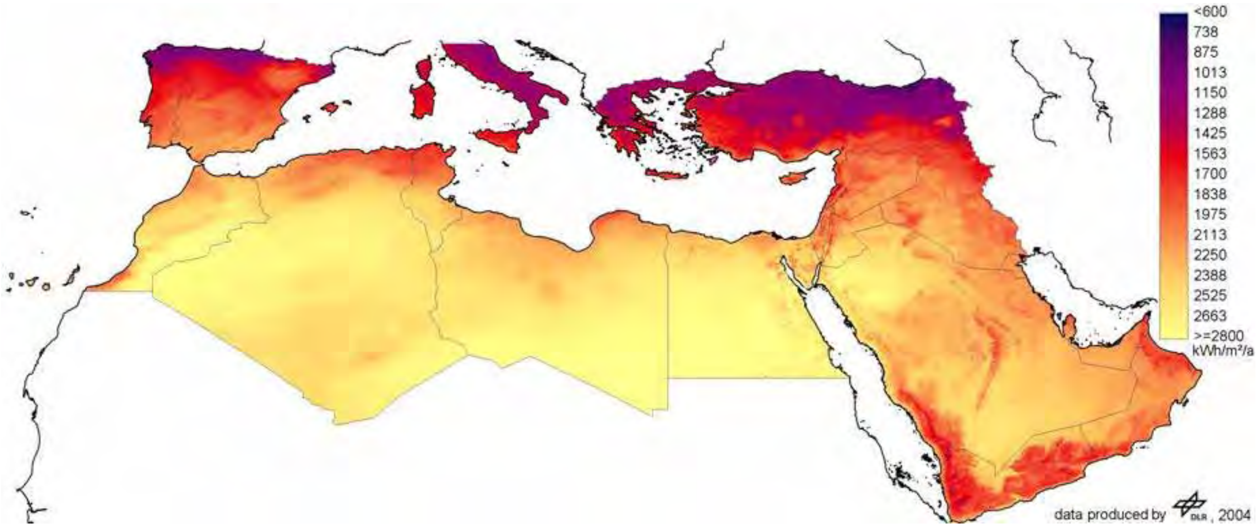


Figure 1-1: Annual Direct Normal Irradiance of the year 2002

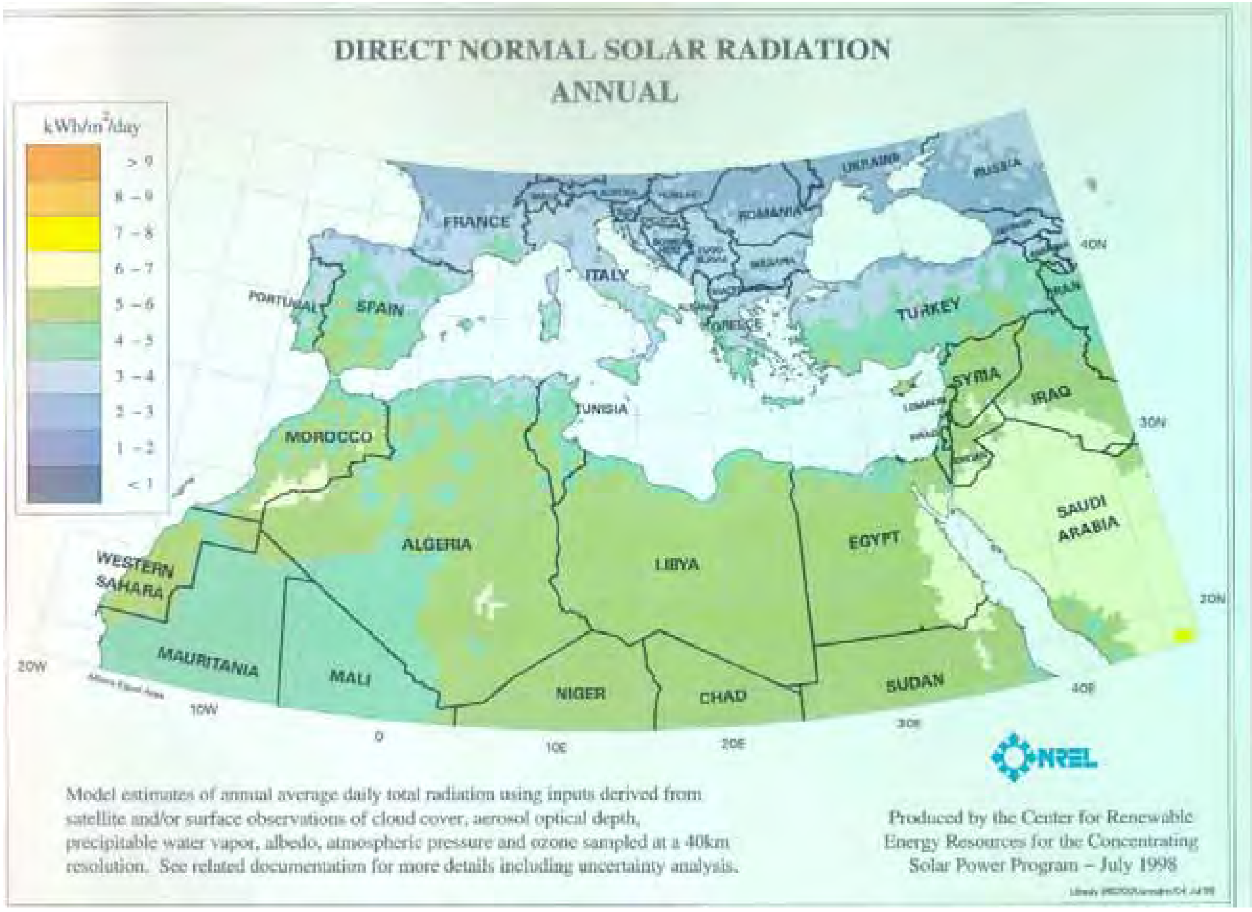


Figure 2 Potential CSP project sites with respect to the exclusion criteria applied for the MENA region:
Source: http://www.dlr.de/tt/Portaldata/41/Resources/dokumente/institut/system/projects/WP3_Resources_Final.doc

“The analysis was performed for the MENA countries for the year 2002. A one-year basis is not sufficient for the development of large CSP projects, as the annual climatic fluctuations can be in the range of ± 15 %. For project development purposes, at least 5-15 years of data should be processed. However, for the assessment of national solar electricity potentials and their geographic distribution, this basis is good enough, especially because in most MENA countries, the total solar energy potential is some orders of magnitude higher than the demand.

The next step is the detection of land resources which allow for the placement of the concentrating solar collector fields. This is achieved by excluding all land areas that are unsuitable for the erection of solar fields due to ground structure, water bodies, slope, dunes, protected or restricted areas, forests, agriculture etc. Geographic features are derived from remote sensing data and stored in a geographic information system (GIS). Finally, those data sets are combined to yield a mask of exclusion criteria for a complete region or country (Figure 3-2). The remaining sites are in principle potential CSP project sites with respect to the exclusion criteria applied.

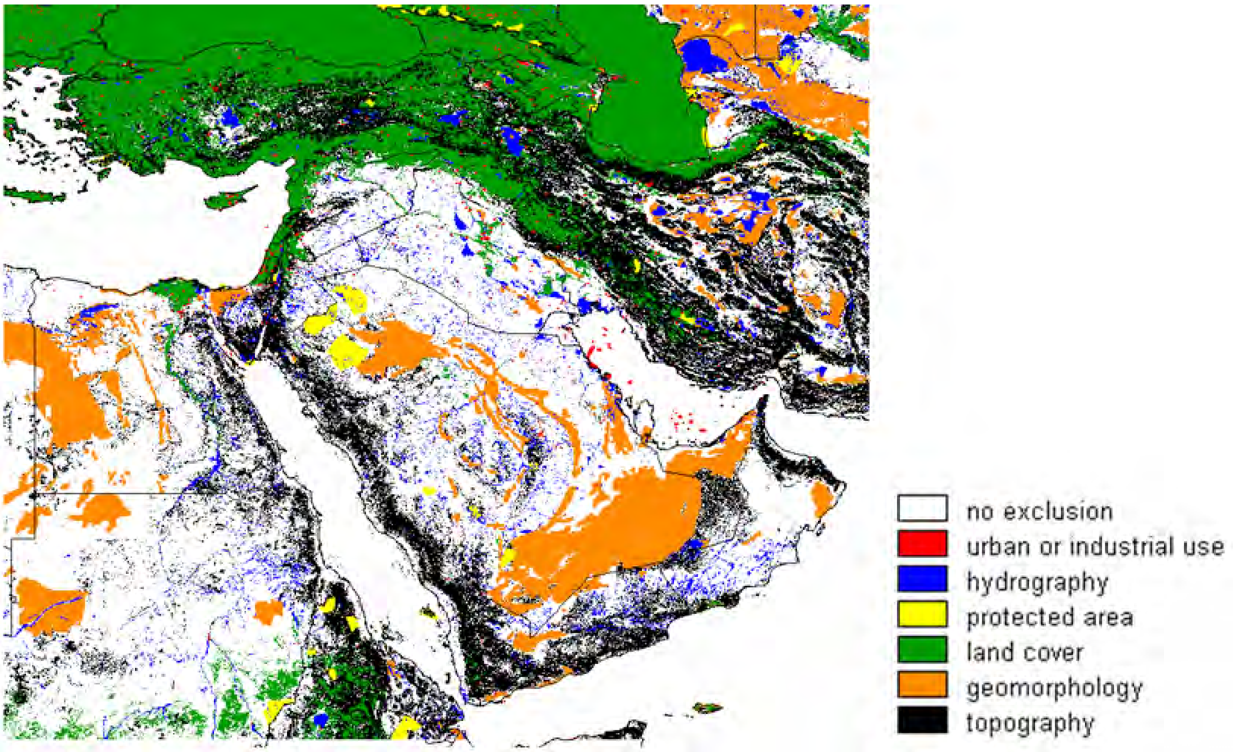


Figure 3-2: Exclusion Areas for Concentrating Solar Thermal Power Plants

3.3. WIND

The performance and structural design of the solar field is impacted by high winds. The solar field is not designed to operate at winds of more than 30 to 70 km/h (depending on the technology choice); consequently, high wind sites limit the performance potential of the solar plant. Moreover, wind forces dictate the collector structural design. Since the structure constitutes about 40% of the solar field cost, it is important both to know the frequency distribution curve of wind velocities and to optimize the structure for these conditions. To know the maximum wind velocities observed is also needed. The solar field is designed to survive wind speeds of (120-130 km/h) with the collectors stowed in non-operating face down position. The solar field can be designed for higher maximum survival wind speed, but at an increased cost.

3.4. Other METEOROLOGICAL CONDITIONS:

Meteorological conditions have both positive and negative impacts on the selection of a solar site. For instance, rain and snow may be effective in washing the mirrors and can help lower plant costs. However, if rainfall and snow occur too frequently, the isolation available to the plant may drop.

Among other negative meteorological conditions are wind, ambient temperature and severe weather. Solar field specifications limit operation of the plant in high wind conditions. The ambient temperature and humidity affect thermal cycle efficiency as with conventional power plants. Severe weather conditions, such as hail, tornadoes, hurricanes and flash flooding, could seriously affect plant operation.

3.4.1. WATER

The water requirements for a concentrating solar power plant are essentially the same as those of a fossil-fueled power plant with a comparable electrical output rating and capacity factor. Both types of plant require cycle heat rejection, service, potable, and cycle makeup water. However, for a CSP plant, additional deionzed water is required for washing the concentrating mirrors. For a CSP plant of about 50 MWe cycle cooling requires approximately 1.000.000 m3 of water per year. The additional solar field washing water requirement, depending on the washing frequency, is typically 3.000 to 8.000 m3 per year.

3.4.2. LAND

The land required for a CSP plant depends on the electrical power output of the plant, the solar multiple and the CSP technology type. (Solar Multiple is defined as the peak thermal power absorbed by receiver divided by the thermal power needed to operate the turbine at its rated load). Typically, a large solar multiple corresponds to a large amount of thermal storage. For example, a plant with a solar multiple of 1.5 may have about three hours of storage; whereas a plant with a solar multiple of 2.1 may have up to nine hours of storage.

The selected plant site should be relatively flat with an allowable slope depending on the CPT technology type (about 1-2% for linear focus and up to 3-4% for point focus technologies). The soil conditions of the plant site determine the types of foundations for the collectors, the heliostats and receiver tower. Also, the seismic risk characteristics of the plant site affect the designs and cost of the equipment supports. Obviously, locations of low seismic risk are preferred.

For a selected site, soil data is required at various locations on site, like:

- Soil type and composition as function of depth (e.g., sand, clay, loam, sedimentary; grain size, density)
- Water table data (well depths, level of water in wells)
- Resistance to penetration (standard blows per foot); Lateral modulus of elasticity, Minimum stress capacity

3.4.3. TRANSPORTATION

A CSP plant is similar to a fossil-fueled power plant in that the proximity of the plant to existing highways and railroads is desirable. Access roads must be suitable for transporting the heavy equipment like turbine generators to the site. Skilled personnel must be available to construct and operate the plants. If possible, the plant site should be located relatively close to a populated area capable of providing construction workers and operating personnel for the plant (as a ratio of about 1 permanent worker per megawat for plant operation and about ten workers per megawatt for plant contruction during the two years of plant erection).

A backup fuel must be available for granting firm power during the times when no solar energy is available.

3.4.4. TRANSMISSION LINES

The location of a CSP plant site close to existing transmission lines is desirable. This minimizes the cost of interfacing the plant's output with the utility grid.

3.4.5. OTHER SITTING CONSIDERATIONS

A variety of other sitting considerations are important to plant design placement. Brief discussion of these factors follows.

- Topography and Surface hydrology:
- Topographical maps (1:200.000-1:500.000 for overview; 1:25.000-1:50.000 for site selection) showing slopes as a function of direction (0.5% slope is desirable; higher slopes up to 3% may be acceptable depending on cost of grading and technology choice; slope in the north-south direction is preferred)
- 50 years and 100-year flood data,
- Aerial photographs (oblique or low-angle views)
- Land ownership and current land use
- Land use priorities or zoning restrictions applicable to this site
- Existing rights of way (water, power line, roads, other access)
- Land cost
- Existence of dust, sand, or fumes carried to site by winds (constituents, quantity or rate, duration, direction, velocity).
- General environmental acceptability in terms of social impacts, water utilization, general ecology, etc.

3.5. Ground measurements of meteorlogical variables for CSP plants

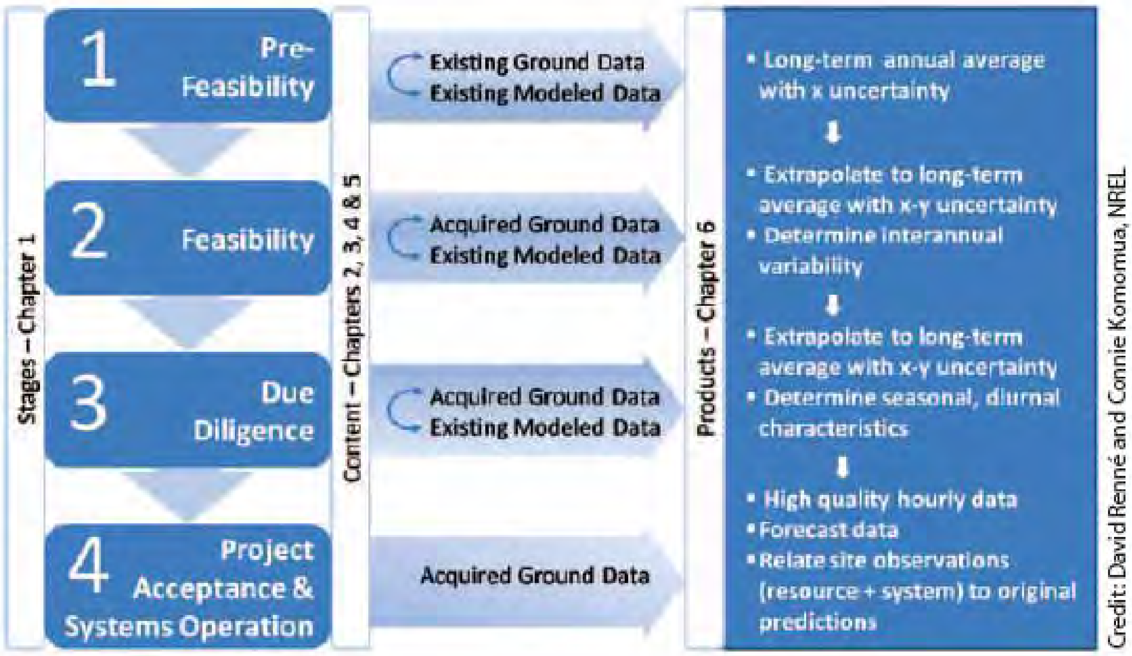
A document from the American NREL (National Renewable Energy Laboratory) explains the "**Best Practices Handbook for the Collection and Use of Solar Resource Data**", for CSP. It is accessible by internet at: http://www.nrel.gov/docs/fy10osti/47465.pdf

"The *Handbook* was developed in response to a growing need by the Concentrating Solar Power community for a single document addressing the key aspects of solar resource characterization".

In its Preface, this NREL report states:

"This handbook presents detailed information about solar resource data and the resulting data products needed for each stage of the project, from initial site selection to systems operations.

It is not meant to be read from cover to cover, but to be used as a reference during each project stage. The figure below lists these stages and shows which chapters contain information about the corresponding available data and resulting products.



As it is stated in the figure, in the Pre-feasibility Stage, all type of available information should be compiled. This may include available information from the Lebanese Meteorological service, the available maps from other sources in the near region, etc.

For the following phases of CSP projects development the acquisition of hourly (and if possible sub-hourly) Ground Data is needed for validate the prediction (within uncertainty analysis) form other measurements and modeled estimations both at totals (annual, monthly and diurnal and dynamic (hourly, 5 to 15 minutely) levels.

As derived from the firs section on “site qualification”, magnitudes to measure are:

- Solar Radiation in redundant way: Direct normal, Global horizontal, ..
- Wind speed and wind direction
- Dry bulb Temperature
- Relative humidity

3.5.1. Measuring Solar Radiation

Chapter 3 of the NREL report describes the procedures for “Measuring Solar Radiation”:

“Accurate measurements of DNI are essential to CSP project design and implementation. Because DNI data are relatively complex, and therefore expensive compared with other meteorological measurements, they are available for only a limited number of locations. Increasingly, developers are in need of DNI data for site resource analysis, system design, and plant operation. DNI measurements are also used to develop and test models for estimating DNI and other solar irradiance components based on available surface meteorological observations or satellite remote sensing techniques. DNI measurements will also play an important role in developing solar resource forecasting techniques.

3.5.2. “Instrumentation Selection Options

Before considering instrumentation options and the associated costs, the user must first evaluate the data accuracy or uncertainty levels that will satisfy the ultimate analyses based on the DNI measurements. This ensures the best value can be achieved after the available various measurement and instrumentation options are considered.

“By first establishing the project needs for DNI accuracy, the user can base instrument selection and the levels of effort for operating and maintaining the measurement system on an overall cost-performance determination. Specifically, “first-class” instrumentation should not be purchased if the project resources cannot support the maintenance required to ensure measurement quality consistent with the radiometer design specifications and manufacturer recommendations.

“Redundant instrumentation is another important consideration to ensure confidence in data quality. Multiple radiometers within the project location and/or providing for the measurement of all three solar irradiance components (GHI, DHI, and DNI), regardless of the primary measurement need, can greatly enhance opportunities for post-measurement data quality assessment.

“Pyrheliometers and Pyranometers

“Pyrheliometers and pyranometers are two types of radiometers used to measure solar irradiance. Their ability to receive solar radiation from two distinct portions of the sky distinguishes their designs. …Pyrheliometers are used to measure DNI and pyranometers are used to measure GHI, DHI, or plane-of-array (POA) irradiances. Table 3-1 summarizes some key attributes of these two radiometers

Table 3-1. Solar Radiation Instrumentation

Radiometer Type	Measurement	FOV(full angle)	Installation
Pyrheliometer	DNI	5.7 degrees to 6.0 degrees	Mounted on automatic solar tracker for alignment with the solar disk
Pyranometer	GHI	2π steradians	Mounted on stable horizontal surface free of local obstructions*
Pyranometer	DHI	2π steradians	Mounted on automatic solar tracker fitted with shading mechanism or on a manually adjusted shadowband platform for blocking DNI from detedtor surface*
Pyranometer	POA	2π steradians	Mounted in the POA of the flat plate solar collector*

- Optionally installed with powered ventilator to reduce contamination of optical surfaces.

“Pyrheliometer and Pyranometer Classifications

“The ISO and the WMO have established classifications and specifications for the measurement of solar irradiance (ISO 1990; WMO 2008). We encourage the reader to review these documents in more detail as part of the project planning for solar resource measurements before acquiring pyrheliometers or pyranometers.

“Estimated measurement uncertainty is the basis for these pyrheliometer and pyranometer classifications. The WMO (2008) recognizes the difficulties associated with measuring solar irradiance:

“It may be said generally that good quality measurements are difficult to achieve in practice, and for routine operations they can be achieved only with modern equipment and redundant measurements. Some systems still in use fall short of best practice, the lesser performance having been acceptable for many applications. However, data of the highest quality are increasingly in demand.

“The WMO characteristics of operational pyrheliometers and pyranometers are presented in Tables 3-2 and 3-3. The ISO specification lists for these radiometers are presented in Tables 3-4 and 3-5. Our purpose for providing these classifications is to address questions about differences in data quality and to give the reader a better understanding of the data quality afforded by particular instrument classes.

Table 3-2. WMO Characteristics of Operational Pyrheliometers for Measuring DNI

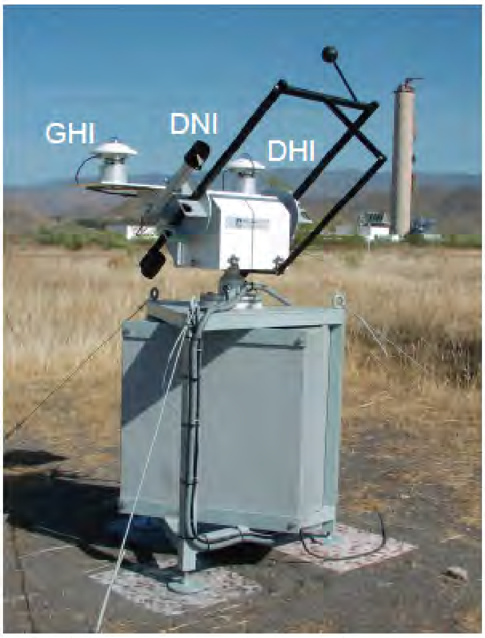
Characteristic	High Quality	Good Quality
Response time(95% response).	< 15 s	<30s
Zero offset – response to 5 k/h change in ambient temperature.	2W/m^2	4W/m^2
Resolution – smallest detectable change in W/m^2.	.051	1
Stability – change per year, percentage of full scale.	.01	.05
Temperature response – percentage maximum error due to any change of ambient temperature within an interval of 50 K.	1	2
Nonlinearity – percentage deviation from the responsivity at 500W/m^2 due to any change of irradiance within the range 100 to 1100W/m^2.	.02	.05
Spectral sensitivity – percentage deviation of the product of spectral absorptance and spectral transmittance from the corresponding mean within the range of 300 to 3000nm.	.05	1.0
Tilt response – percentage deviation from the responsivity at 0 degrees tilt (horizontal) due to change in tilt from 0 degrees to 90 degrees at 1000W/m^2.	.02	.05
Achievable uncertainty (95% confidence level):		
1-min totals		
Percent	0.9	1.8
KJ/m^2	0.56	1
Wh/m^2	0.16	0.28
1-h totals		
Percent	0.7	1.5
KJ/m^2	21	54
Wh/m^2	5.83	15.0

Table 3-3. WMO Characteristics of Operational Pyranometers for Measuring GHI or DHI

Characteristic	High Quality	Good Quality	Moderate Quality
Response time – 95% response	< 15 s	< 30 s	< 60 s
Zero offset Response to 200 W/m² net thermal radiation (ventilated) Response to 5 K/h change in ambient temperature	 7 W/m² 2 W/m²	 7 W/m² 2 W/m²	 7 W/m² 2 W/m²
Resolution – smallest detectable change	1 W/m²	5 W/m²	10 W/m²
Stability – change per year, percentage of full scale	.08	1.5	3.0
Directional response for beam radiation – the range of errors caused by assuming that the normal incidence Rs is valid for all directions when measuring, from any direction, a beam radiation whose normal incidence irradiance is 1000 W/m²	10 W/m²	20 W/m²	30 W/m²
Temperature response – percentage maximum error due to any change of ambient temperature within an interval of 50 K	2	4	8
Nonlinearity – percentage deviation from the Rs at 500 W/m² caused by any change of irradiance within the range of 100 to 1000 W/m²	.05	1	3
Spectral sensitivity – percentage deviation of the product of spectral absorptance and spectral transmittance from the corresponding mean within the range 300 to 3 000 nm	2	5	10
Tilt response – percentage deviation from the Rs at 0 degrees tilt (horizontal) caused by change in tilt from 0 degrees to 90 degrees at 1000 W/m²	0.5	2	5
Achievable uncertainty – 95% confidence level Hourly totals Daily totals	 3% 2%	 8% 5%	 20% 10%

Figure 3-4. Pyrheliometers mounted on automatic solar tracker

Precise sensors *(also for calibration of RSP)*:



Thermal sensors:
pyranometer and pyrheliometer,
precise 2-axis tracking

Advantage:

+ high accuracy
+ separate GHI, DNI and DHI sensors
  (cross-check through redundant measurements)

Disadvantages:

- high acquisition and O&M costs
- high susceptibility for soiling
- high power supply

“Rotating Shadowband Radiometers

“Rotating shadow band radiometers (RSRs) use a pyranometer that is periodically shaded by a motorized shadow band that moves across the detector’s FOV (Figure 3-12). By design, the instrument measures GHI when unshaded and DHI when shaded. …Although this instrument is motorized and requires energy for electronics necessary to operate the system, the electrical power requirements of some commercially available units is low enough to be powered by a small photovoltaic (PV) panel and storage battery. Such a design is well suited for remote installations where conventional power is not available.

Figure 3-12. Two commercially available RSRs: Irradiance, Inc. Model RSR (left) and Yankee Environmental Systems, Inc. Model SDR-1 (two units shown on right)

Instrumentation for unattended abroad sites:

Rotating Shadowband Pyranometer (RSP)

Sensor: Si photodiode

Advantages:

+ fairly acquisition costs
+ small maintenance costs
+ low susceptibility for soiling
+ low power supply

Disadvantage:

- special correction for good accuracy necessary *(established by DLR)*

3.5.3. Resources and suppliers

http://www.meteo-technology.com/solar.htm:. This site offers information about meteorological instruments and observing systems. Meteorological sensors, instruments, weather stations, and meteorological measurement systems

http://www.meteo-technology.com/company_address.htm#ki :Database of companies that are active in the meteorological field with e-mail and url

Additionally, the attached file includes a set of annexes with several examples of meteorological stations suppliers, together with the guidebook "CONCENTRATING SOLAR POWER - Best Practices Handbook for the Collection and Use of Solar Resource Data" published by NREL in 2010.

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[i] http://www.solarpaces.org/ANDASOL.HTM.

[ii] http://www.energylan.sandia.gov/sunlab/PDFs/solar_tower.pdf.

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