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FUTURE SUSTAINABLE CONCENTRATING SOLAR POWER TECHNOLOGIES: A REVIEW

A.M.K. El-Ghonemy
High Institute of Engineering and Textile Technology, Egypt
Email: amghonemy@yahoo.com

Abstract: Concentrating solar thermal power is a renewable energy (RE) technology which converts solar irradiation into heat energy at high temperature and in a successive step into electricity. The core part is a number of mirrors which reflects direct normal irradiance (DNI) to a focal line or point, called a receiver. Temperatures up to 1000 ^{o}C can be achieved. These plants make use of conventional steam cycles, in which hybrid operation with fossil fuels is applicable. The key advantage of CSP in comparison to other RE technologies is that the need for fossil fuel can be reduced by over sizing the solar collector field and storing the extra heat. This paper is directed to provide a comprehensive review of CSP technologies that are sustainable for applications in MENA region. More focus was directed to the performance data with emphasis on technologies, economics and costs. A comparative study between different CSP technologies as well as performance and economics has been done. Finally, some general guidelines are given for the selection CSP systems and the parameters that are needed to be considered for decision makers.

الملخص:

تعتبر تقنية توليد الطاقة الحرارية من الطاقة الشمسية المركزة (المجمعات الشمسية) احدى أنواع الطاقة المتجددة – حيث تعمل أنظمة المركزات الشمسية على تحويل الاشعاع الشمسى الى طاقة حرارية عند درجات حرارة مرتفعة – ثم يتم تحويلها الى كهرباء كمرحلة تالية. حيث يمثل المجال الشمسى (مجموعات من المجمع الشمسى) العنصر الرئيسى والذى يقوم بدوره فى عملية انعكاس أشعة الشمس االتى تسقط عليه مباشرة وتجميعها على خط البؤرة وهو مايسمى بالمسقبل . من الجدير بالذكر أنه باستخدام هذه التقنية يمكن الوصول الى درجات حرارة تصل الى 1000درجة مئوية – وهو مايعنى امكانية تكامل هذه المركزات الشمسية مع محطات التوليد التقليدية والاستفادة بربط هذه النظم بالشبكة الكهربية. أيضا تمتاز هذه المحطات الشمسية بامكانية استخدام الوقود الأحفورى كمصدر مساعد واضافى عند الضرورة (دروة مهجنة) .

كما أنه تجدر الاشارة الى أنه من أهم مايتميز به هذا النوع من المحطات الشمسية عن باقى أنواع الطاقة المتجددة هو أنه يمكن مضاعة حجم المجمعات الشمسية المطلوبة لادارة المولد التربينى - وتخزين هذه الطاقة الزائدة فى صورة حرارية لتقليل استهلاك الوقود الأحفورى.

وقد تم تخصيص هذه الورقة البحثية لعمل مراجعة نقدية شاملة للتقنيات المتعلقة بتطبيقات استخدام الطاقة المستدامة من أشعة الشمس الحرارية فى اقليم الشرق الأوسط وشمال أفريقيا. وقد تم التركيز على بيانات الأداء للتقنيات المختلفة والاقتصاديات والتكاليف . أيضا تم اجراء دراسة مقارنة بين مختلف تقنيات الطاقة المستدامة من أشعة الشمس الحرارية من حيث الأداء والاقتصاديات . وفى النهاية تم الاشارة الى بعض الارشادات العامة المفيد اتباعها عند اختيار نظم الاستفادة من الطاقة المستدامة من أشعة الشمس الحرارية - الى جانب المؤشرات الهامة الواجب أخذها فى الاعتبار عند اختيار هذا النوع من المحطات - والتى تسهم فى توجيه السياسات وترشيد جهود صناعة القرار.

***Keywords*:** Concentrated Solar Power (CSP) Plant, Concentrated Solar Collectors (CSCs), Power Generation.

1. Introduction

1.1. Principle of concentrating solar power (CSP)

The main element is a field of large mirrors reflecting the incident sun rays onto a small receiver element, thus concentrating the solar radiation intensity by 80 to several 100 times and producing high temperature heat at several 100 to over 1000 °C. This heat can be either used directly in a thermal power cycle (based on steam turbines, gas turbines or Stirling engines), or stored (in molten salt, concrete or phase-change material) to be delivered later to the power cycle for night-time operation [1].

The principle of operation of a concentrating solar power (CSP) plant is drafted in Figures (1), showing the different options for combined generation of heat and power.

CSP plants can be designed from 5 MW up to several 100 MW of capacity [1].

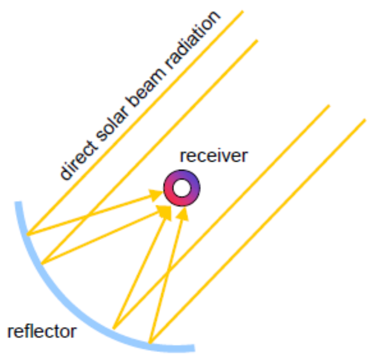

Figure (1-a): *principle of a concentrated Solar collector [1].*

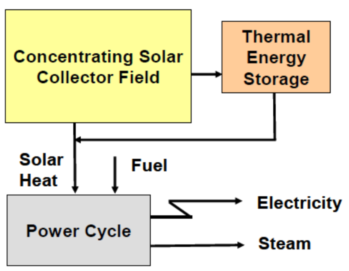

Figure (1-b): *A concentrating solar thermal power station for co-generation of electricity and process steam*

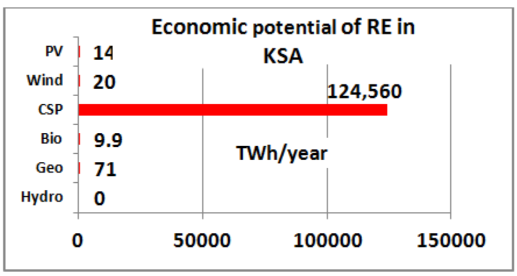

Figure (2): *Economical potential for different RE*

1.2. Why MENA Regions

All Middle East and North Africa (MENA) regions have an outstanding potential for solar energy. Growth of population and economy, increasing urbanization and industrialization, against the limited natural resources of potable water and energy in MENA are leading to serious deficits. Generally, all CSP technologies can be used for generating electricity and heat. However, the more focus is on CSP for Electricity production, HVAC and the production of safe drinking water because these constitute major needs of developing countries (MENA. Consequently, the bulk of this new CSP capacity is expected to be seen in the MENA region, where it has abundant solar radiation (fig.3), cheap land and high electricity demand) [1]. The economic potential of renewable energy (RE) in Saudi Arabia is illustrated in figure (2) [11]. From this figure, it is clear that CSP has the highest economic potential.

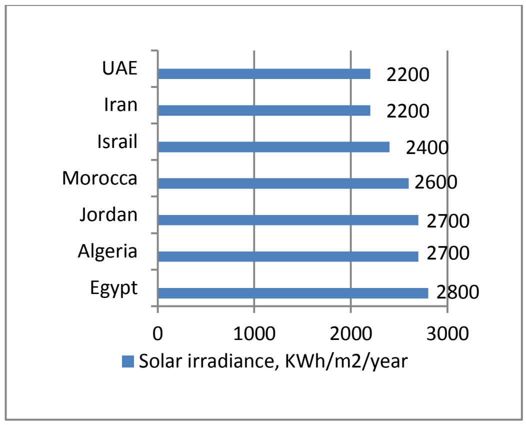

Fig (3): *Solar irradiance for different countries, kWh/m^2/year [14-16].*

1.3. CSP Market for MENA Region [15-16]

The CSP global capacity is expected to reach 13 GW by year 2015, indicating that solar CSP is moving to the forefront of renewable energy technologies. The bulk of this new capacity is expected to be seen in the MENA region, where it has abundant solar radiation, cheap land and high electricity demand.

Table (1): *Announced capacity for electricity from CSP[14-16].*

location	Solar irradiance, kWh/m^2/year	Planned CSP capacity(MW)	Economic potential, TWh	Technical potential, TWh
Algeria	2700	255	168972	169440
Egypt	2800	30	73656	73656
Morocco	2600	30	20146	20151
UAE	2200	100	1988	2078
Jordan	2700	30	6429	6434
Iran	2200	70	20000	>20000
Israel	2400	100	318	318

1.4. Objectives

This paper is directed to provide a comprehensive review of CSP technologies that are sustainable for applications in MENA regions, where it has abundant solar radiation, cheap land and high electricity demand.. More focus is directed to the performance data with emphasis on technologies economics and costs.. A comparative study between different CSP technologies as well as performance and economics has been done. Finally, some general guidelines are given for the selection CSP systems and the parameters that are needed to be considered.

2. Basics and Types of CSP [1-18]

Four primary CSP designs are available in the market today:

- Parabolic troughs (PT),
- Linear-Fresnel systems (LF),
- The Stirling engine (SE), and
- Solar towers (ST).

In parabolic trough systems, each trough has its own receiver, while Fresnel reflectors are made of many thin, flat mirror strips to concentrate sunlight onto common tubes through which a working fluid is pumped.

A Stirling dish or dish engine system consists of a stand-alone parabolic reflector that concentrates light onto a receiver positioned at the reflector's focal point.

In tower systems, thousands of tracking mirrors in a field capture and reflect sunlight to a central receiver located at top of the tower. The different types of concentrating technologies are summarized in table (2).

Recently, more focus has been given to the parabolic trough (PT) concentrated solar thermal system (PT-CST). This technology fits well with the special needs of developing countries as a ready source of energy for water desalination and HVAC applications.

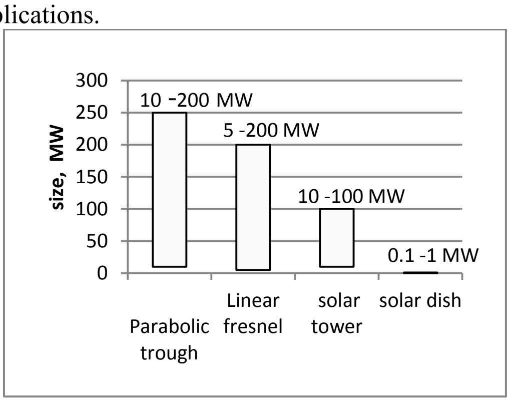

Fig.(4a):*Capacity figures for different CSP technologies*

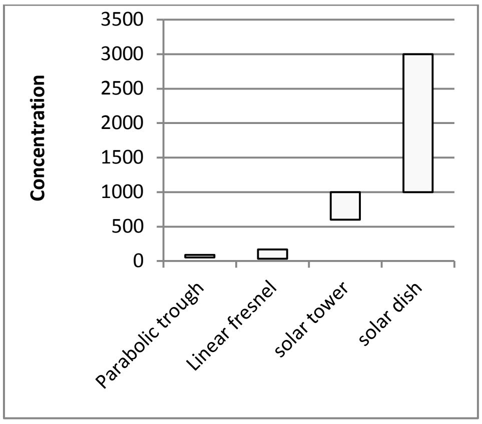

Fig.(4b):*Concentration factor for different CSP technologies.*

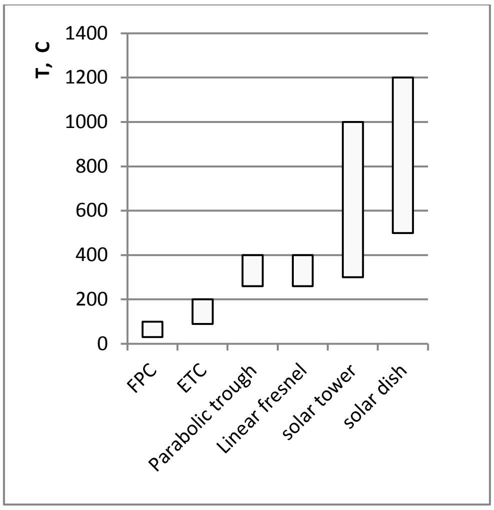

Fig.(4c):*Achievable Temperatures for different CSP technologies (FPC =Flat plate collector, ETC = Evacuated tube collector).*

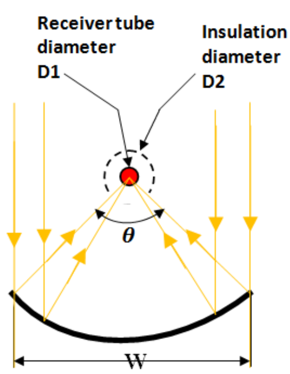

Figure (5): *Back reflecting parabolic trough [4].*

Table (2). *Concentrating solar technologies [2,4].*

Optical method		focus	Temperature (^{0}C)	Heat transport to boiler
1	Parabolic trough mirror	line	300-550	Oil, liquid salt, water+steam
2	Linear Fresnel mirror a	line	250-500	Water+steam
3	Linear Fresnel lens b	line	250-400	Water+steam
4	Solar tower with field of heliostats	point	300-1000	Air, liquid salt, water+steam, gas turbine
5	Solar dish	point	400-1500	Stirling engine
6	Fresnel lens	point	400-1200	Micro turbine

3. Solar Collectors[4,5,19-23]

Focusing or Concentrating, collectors intercept direct solar radiation over a large area and focus it onto a small absorber area, see figure (5). These collectors can provide high temperatures more than flat-plate collectors.

However, diffused solar radiation cannot be focused onto the absorber. Most concentrating collectors require mechanical equipment in order to orients the collectors toward the sun and keeps the absorber at the point of focus. Therefore, there are four basic types of concentrating collectors:

- Stationary concentrating collectors
- Parabolic trough, figure (6).
- Power tower, figure(7)
- Parabolic dish, figure(8)

Typical performance parameters of various solar collectors are listed in tables(3).

Table (3). *Typical concentration range and temperatures of various solar collectors[5, 19-23].*

Technology	T, ºC	Concentration ratio	tracking	Max. conversion Efficiency,%(Carnot)
Flat plate collector	30-100	1	-	21%
Evacuated tube collector	90-200	1	-	38%
Solar Pond	70-90	1	-	19%
Solar chimney	20-80	1	-	17%
Fresnel reflector	260-400	8-80	one-axis	56%
Parabolic trough	260-400	8-80	one-axis	56%
Heliostat field+ central receiver	500-800	600-1000	Two-axis	73%
Dish concentrator	500-1200	800-8000	Two-axis	80%

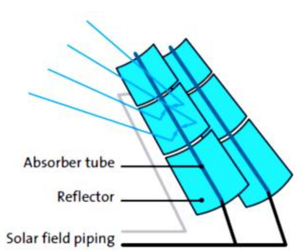

Figure (6). *Schematic of PTC [16].*

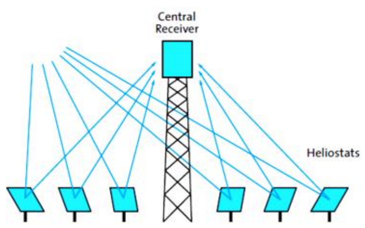

Figure (7). *Schematic of solar tower [16].*

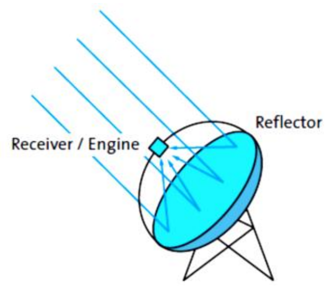

Figure (8).*Schematic of solar dish [16].*

4. Main Components of CSP Systems

Some of the components like the metal structure, the tracking system, controllers and other accessories, which make up to 60% of the direct solar field costs, are standard components and can be ordered from several countries and in different forms. However, reflectors and the absorber tube are special components and have to be produced specifically for the parabolic trough solar field. Main components of

CSP system are listed below, (figure (9)):

1 Solar field collectors
2 Absorber/receiver
3 Heat transfer medium
4 Tracking system (single or double axis)
5 Balance of System
6 In case of power generation, the following components are included:
7 Steam turbine
8 Generator

a. Reflectors (concentrators)

The concentrators consist of a heat formed glass cake. Glass, which is used in solar applications, must have very low iron content for getting a transmissivity in the solar spectrum of about 91%. The iron content of a so-called "White Glass" is about 0.015% compared to normal glass with an iron content of around 0.13%. The binding of the reflectors is done under heat conditions. Several safety layer coatings are added, giving additional protection for the mirror. Finally the contour accuracy is tested using a laser beam.

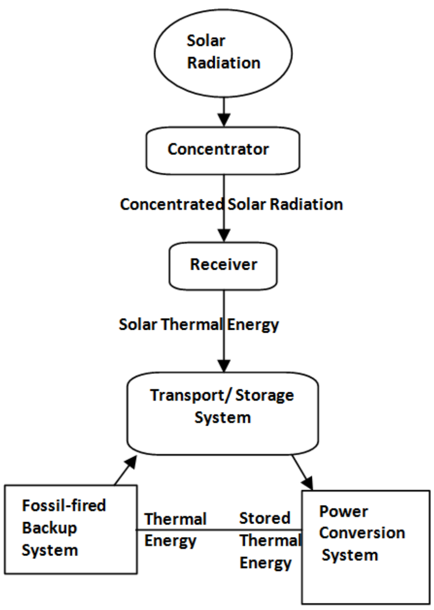

Figure (9).*Main components of CSP system*

b. Absorber

The absorber pipe consists of a stainless steel tube with a length of 4 meters and a thickness of 70 mm. A glass pipe surrounds the tube (see figure 10) to allow evacuating of the area between the absorber tube and the glass pipe in order to minimize convection and conduction heat losses.

c. Receiver

The design of cylindrical cavity receivers is based on the concept of capturing the radiation in an insulated enclosure with an aperture that allows the inlet of the concentrated radiation beam (Figure 11). The working fluid flows axially in the annulus and extracts the energy from the cavity walls. The concentrated radiation focus is located at the cavity entrance. The interior of the cavity is painted with a black coating. No special coatings are required because the emittance of this coating is not critical for thermal losses.

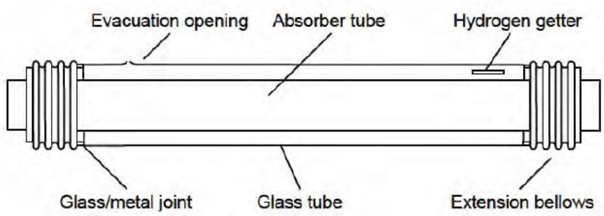

Figure (10).*Absorber tube of a parabolic trough collector [66].*

The vacuum also serves to protect the highly sensitive coating. Nowadays, such selective coatings remain stable in temperatures of 450°C up to 500°C. The average solar absorptivity is currently above 95%, an operational temperature is about 400°C, and the emissivity is below 14%. This leads to an optical efficiency of about 80% for incident perpendicular solar radiation. Furthermore the hydrogen getter (see figure 10) absorbs the hydrogen, which is getting through the glass pipe and the stainless steel pipe by diffusion. A membrane is used to pump the hydrogen out of the vacuum. Finally, glass/metal joints are used to compensate the thermal expansion of the pipe, and the connection between the glass pipe and the metal structure.

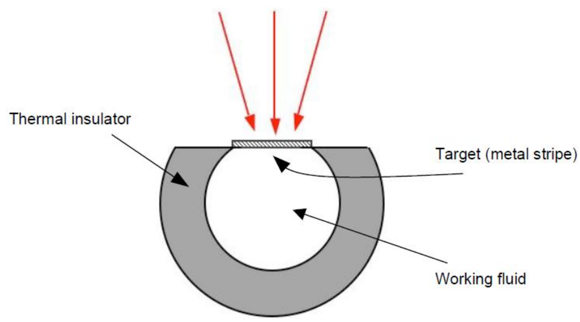

Figure (11).*Cross section of tubular receiver [66].*

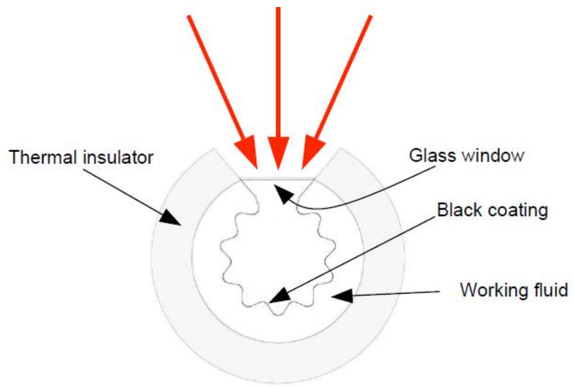

Figure (12).*Cross section of cylindrical cavity receiver [66]*

5. Examples of Specific CSP Power Plants

Examples of specific large solar thermal projects that are currently under construction or in advanced stage are given below:

- Algeria: 140 -150 MW, Integrated solar combined cycle (ISCC) plant with 25 MW solar capacity (trough)
- Egypt: 150 MW ISCC plant with 30 MW solar capacity (trough)
- Greece: 50 MW solar capacity using steam cycle (trough)
- India: 140 MW ISCC plant with 30 MW solar capacity (trough)
- Italy: 40 MW solar capacity integrated into existing combined cycle plant (trough)
- Mexico: 291 MW ISCC plant with 30 MW solar capacity (trough)
- Morocco: 220 MW ISCC plant with 30 MW solar capacity (trough)
- Spain: over 500 MW solar capacity using steam cycle (4 x 10-20 MW solar tower and 12 x 50 MW parabolic trough)
- USA: 50 MW solar capacity with parabolic trough in Nevada using steam cycle, preceded by a 1 MW parabolic trough demonstration plant using ORC turbine in Arizona
- USA: 500 MW Solar Dish Park in California, preceded by a 1 MW(40 x 25 kW) test and demo installation

6. CSP Current Performance [29-34]

The current performance of the four CSP technology families is summarized in Table (4). PT plants are in use of commercial application. ST plants are currently making the transition to commercial application, and linear Fresnel and parabolic dishes are at the demonstration stage, and have not yet reached large-scale commercial application.

Table (4).*Current performance of CSP technology families.*

CSP technology	Peak solar to electricity conversion efficiency (%)	Annual solar-to electricity efficiency (%)	Water consumption, for wet/dry cooling (m^3/MWh)
Parabolic troughs (PT)	23–27	15–16	3–4/0.2
Linear Fresnel (LF) systems	18–22	8–10	3–4/0.2
Solar Towers (ST)	20–27	15–17	3–4/0.2
Parabolic dishes	20–30	20–25	<0.1

Performance data for PT, LF and ST are obtained from commercial plants based on a Rankine cycle and using synthetic oil or steam as HTF. Data for parabolic dishes are based on dish-Stirling systems.

7. Comparison of CSP Technologies [1-10]

A comparison of the key parameters of the four types of CSP technologies is summarized in tables (5).

Table (5). *Key Performance data of various CSP technologies [3,6]*

	Unit Capacity MW	Concentration	Peak Solar Efficiency	Annual Solar Efficiency	Thermal Cycle Efficiency	Capacity Factor (solar)	Land Use (generation weighted) m²/MWh/y
Trough	10 – 200	70 - 80	21% (d)	10 – 15% (d)	30 – 40 % ST	24% (d)	6 – 8
				17 – 18% (p)		25 – 90% (p)	
Fresnel	10 - 200	25 - 100	20% (p)	9 - 11% (p)	30 - 40 % ST	25 - 90% (p)	4 - 6
Power Tower	10 – 150	300 – 1000	20% (d)	8 – 10 % (d)	30 – 40 % ST	25 – 90% (p)	8 - 12
			35 % (p)	15 – 25% (p)	45 – 55 % CC		
Dish-Stirling	0.01 – 0.4	1000 – 3000	29% (d)	16 – 18 % (d)	30 – 40 % Stirl.	25% (p)	8 - 12
				18 – 23% (p)	20 – 30 % GT		

(d) = demonstrated, (p) = projected, ST: steam turbine, GT: Gas Turbine, CC: Combined Cycle. Solar efficiency = net power generation / incident beam radiation, Capacity factor = solar operating hours per year / 8760 hours per year.

8. CSP Applications for MENA Region [41-57]

Electricity generation, HVAC, and the production of safe drinking water are the more focus on CSP applications, because these constitute the major needs in developing countries (MENA). The three major subsystems are shown in figure (13).

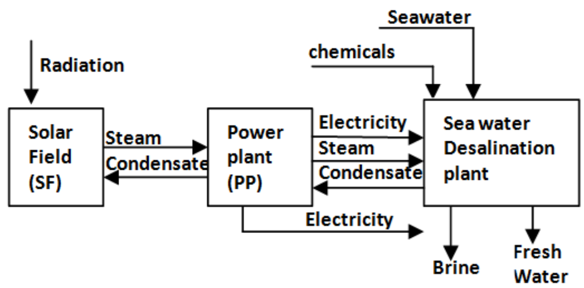

Figure (13). *Block diagram of the solar thermal cogeneration system [31].*

8.1. CSP application in Water Desalination

Three different options for a combination between CSP technologies and desalination were addressed in Figure (14):

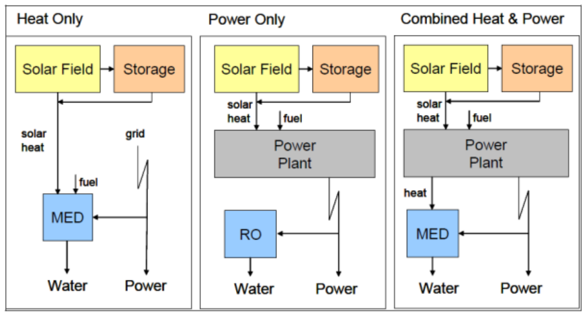

Figure (14). *Different configurations for desalination by concentrated solar power [1,5-9](RO=reverse osmosis, MED=multi-effect desalination).*

1. small-scale desalination plants directly powered by concentrating solar thermal collectors,
2. CSP plants providing electricity for reverse osmosis desalination (CSP/RO).
3. Combined generation of electricity and heat for thermal multi-effect desalination systems (CSP/MED).

Although Multi-Stage Flash (MSF) desalination is the common type in the MENA region, it has not been considered as viable future option for solar powered desalination. This is due to the higher temperature requirement of the MSF process compared to that of MED system.

Table (6). *Overview on market available thermally driven cooling systems based on sorption technology [22].*

Type of system	Water chillers (closed thermodynamic cycles)						Direct air treatment (open thermodynamic cycles)	
Physical phase of sorption material	Liquid	Liquid	Liquid	Solid	Solid	Solid	Liquid	solid
Sorption material	water	Lithium bromide	Lithium bromide	zeolite	Silica gel	Lithium chloride	Lithium-chloride	Silica gel (or zeolite), Cellulose matrix with Lithium-chloride
Refrigerant	Ammonia	Water	Water	Water	Water	Water	Water	Water
Type of cycle	1-effect	1-effect	2-effect	1-effect	1-effect	1-effect	Cooled sorption process	Desiccant rotor
$EER_{thermal}$ ratio	0.5-0.75	0.65-0.8	1.1-1.4	0.5-0.75	0.5-0.75	0.5-0.75	0.7-1.1	0.6-0.8
Driving temperature range, ^{o}C	70-100 120-180(SAT)	70-100	140-180	65-90	65-90	65-90	65-85	60-80
Solar collector technology	FPC, ETC, SAT	FPC, ETC	SAT	FPC, ETC	FPC, ETC	FPC, ETC	FPC, ETC, SAHC	FPC, ETC, SAHC

FPC=Flat plate collector, ETC=evacuated tube collector, SAT=single-axis tracking solar collector, SAHC=solar air heating collector.

8.2. CSP application in Cooling Technology

Generally the solar cooling system comprises of three sub-systems: the solar energy conversion system, refrigeration system, and the cooling load. The different ways to convert solar radiation into cooling and air conditioning are shown in Figure (15) and detailed in table (6).

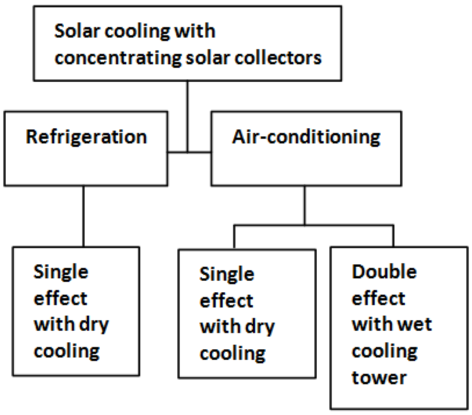

Figure (15).*Categories of high temperature solar cooling systems utilizing concentrating solar collectors [35-40].*

Solar energy can be converted into cooling using two main principles:

1 Electricity generated with photovoltaic modules can be converted into cooling using well-known refrigeration technologies that are mainly based on vapor compression cycles.

2 Heat generated with solar thermal collectors can be converted into cooling using thermally driven refrigeration or air-conditioning technologies. Most of these systems employ the physical phenomena of sorption in either an open or closed thermodynamic cycle. Other technologies, such as steam jet cycles or other cycles using a conversion of heat to mechanical energy and of mechanical energy to cooling are less significant.

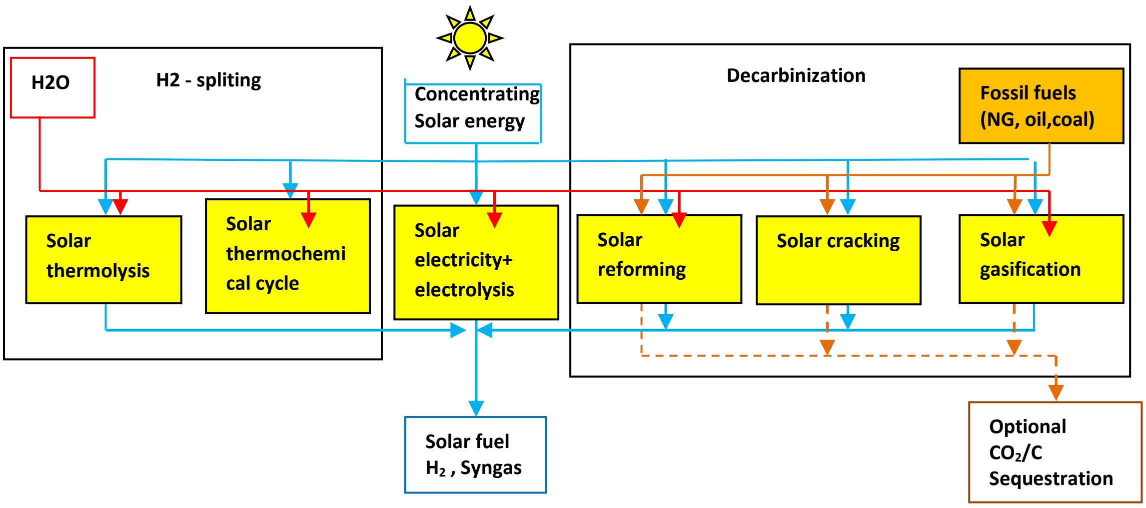

Figure (16). *Different thermo-chemical methods for producing fuels using CSP [roadmap2010 [16]).*

8.3. CSP Application in H2 Technologies

CST technologies also allow the production of Hydrogen (H2), which is considered as a form of storing solar energy. Then it can be distributed as a fuel to industry, households, etc. Production of solar hydrogen can be achieved via electrolysis of water using solar-generated electricity at an overall solar to hydrogen efficiency of about 10%. Several options for H2 production using CSP are outlined in Figure (16).

9. Pre-Selection of CSP Technologies [1]

The aim of pre-selection here is to find the best suited CSP-technology that can be used with seawater desalination (with respect to performance and cost), see figure (17).

On the other hand, neither PT nor LF systems can be used to power gas turbines. In the high - temperature range up to 1000 °C and more, central receivers are the only available option to provide solar heat for gas turbines and combined cycle systems. However, it is still uncertain and still leaves open questions with respect to cost, reliability and scalability for mass production at large scale.

Looking at Table (7) the LF beats the PT with synthetic oil as heat transfer medium in many items. However, the most important issues like experience, reliability and availability of TES, the linear Fresnel system is in an inferior position compared to the parabolic trough system. This fact is not compensated by the less cost of the solar field of the linear Fresnel system.

Parabolic trough power plants represent about 88 % of the worldwide installed CSP capacity and about 97.5 % of all capacity which is currently under construction (CSP Today, 2011).

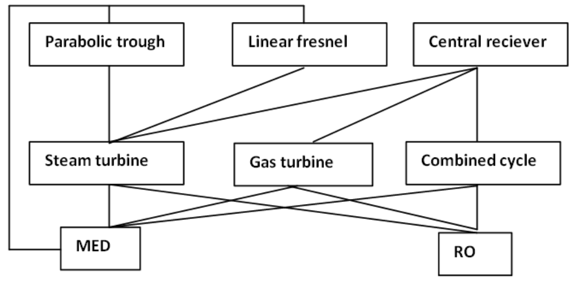

Figure (17): *Options of large scale concentrating solar power and desalination systems [1].*

Table (7).*Characteristics of current concentrating solar power technologies (PCM: Phase Change Materials) [35-40].*

Concentration Method	**Line Concentrating Systems**			**Point Concentrating Systems**		
Technology	**Parabolic Trough**		**Linear Fresnel**	**Central Receiver**		**Parabolic Dish**
Heat Transfer Fluid	Synthetic Oil	Water / Steam	Water/Steam Superheated and saturated Steam Cycle	Water/Steam, Air	Pressurized Air	Air
Power Cycle	Superheated Steam Cycle	Superheated Steam Cycle	Superheated and saturated Steam Cycle	Superheated and saturated Steam Cycle	Gas Turbine and Combined Cycle	Stirling Engine
Crucial Criteria						
Typical Unit Size (MW)	10 - 250	10 - 250	5 - 200	10 - 100	5 - 100	0.1 - 1
State of the Art	commercial	experimental	recently commercial	semi-commercial	experimental	demonestrated
Cost of Solar Field (€/m²)	300 - 350	n. a.	200 - 250	300 - 400	300 - 400	n.a
Investment Costs (€/kW) for SM1 - SM2	3,500 - 6,500	n. a.	2,500 - 4,500	4,000 - 6,000	n.a.	6,000 - 10,000 (only SM1)

10. Solar Tracking [3, 58-59]

The concentrating collectors can be operated in three modes:

a- Fixed orientation mode.

At solar noon, the range of solar elevations during the year is $\pm 23.45^{o}$. Thus, a collector with fixed orientation must have an acceptance aperture half-angle of at least 23.45^{o}.

For continuously tracking system, the acceptance aperture needs only to be large enough to include the solar disc; plus errors on mirrors or lens construction and errors in collector steerage orientation. This easily allows concentration ratios in the range of 5-15 and intermediate temperatures are also achievable.

b- Continuous tracking mode.

c- Periodic seasonal adjustment mode,

For periodic adjustment or fixed orientation, the concentrators must be two-dimensional, with long axis in the east-west direction.

As the first example, compound parabolic collector (CPC) must be reoriented periodically during the year to keep the sun within their ranges of acceptance. Collector with large acceptance angles needs less adjustment during the year.

The second example is Fresnel lens collectors with the main axis in the north-south orientation. In this configuration, the north end must be elevated so as to tilt the collector. The yearly optical efficiencies are shown in table (8)

Table (8).*relative yearly optical efficiencies of Fresnel lens systems [4].*

Lens configuration	**Relative efficiency**
Two-axis tracking(N/S)	1
Seasonally adjusted(N/S)	0.95
Fixed tilt(N/S)	0.7
One axis tracking	
One axis tracking(E/W)	0.6
Seasonally adjusted(E/W)	0.5

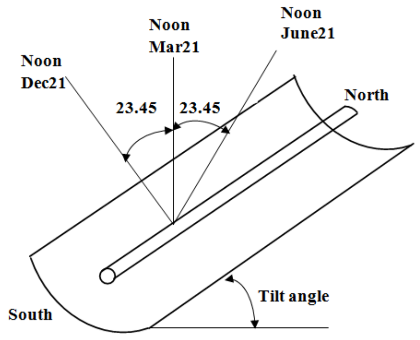

Figure (18).*PTC with long axis in the N-S direction [4].*

The third example is parabolic trough collector (PTC). It can be mounted in several different ways. The most common method is to mount the collector horizontally with the long axis in the east-west direction as shown in figure(18).it can also be mounted with the long axis with the north-south direction. The tilt angle is a very important parameter for north-south direction. East-west orientation collects roughly equal amount of on clear days for all days of the year. While, north-south orientation collects very strongly in the summer and very weekly in the winter, as indicated in figure(19)

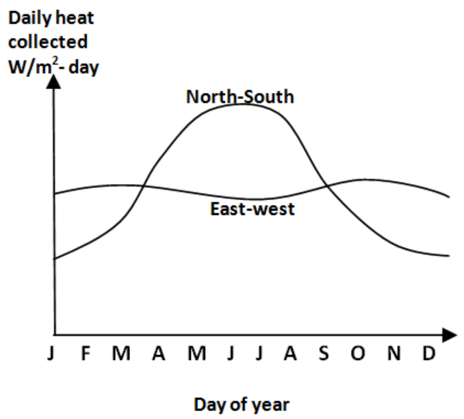

Figure (19).*Estimated heat collection of a horizontal PTC per day per unit area of aperture on clear days [4].*

10.1. Solar Tracking Methods

Solar tracking methods are passive, using an open-loop approach or active using a closed loop [6]. Passive tracking methods employ Astronomical algorithms (AA) and compute the solar position as a function of position and time. This type of positioning is limited in precision and depends only on the precision of the algorithms, provided that electro-mechanic precision is acceptable. For this type of positioning, the azimuth axis vertical alignment and zenith horizontal alignment is of crucial importance to the overall tracking accuracy [6].

Active tracking methods use light sensitive electronics to see the sun and position themselves in a very dynamic way to the best position. Restrictions applying to this type of tracking are in the sensitivity of the sensors and the level of intelligence of the control system.

Active tracking methods work in the approach of brightest point in the-sky. Thus, unwanted movement of the device in cloudy conditions can be expected, leading to increased power consumption, mechanical wear. The precision range of active tracked systems is between 0.2 to several degrees, depending on the system design.

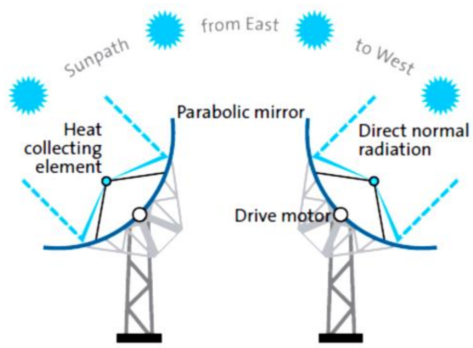

Figure (20). *Daily tracking of PT collectors [60,61].*

11. Economics [1-10, 3, 60, 61]

11.1. The current cost of CSP [3]

According to the International Energy Agency (IEA, 2010) and National renewable energy Laboratory (NREL), costs of CSP plants can be grouped into three categories:

- Investment costs (also called capital cost or CAPEX),
- Operation and maintenance costs (O&M) which is so called OPEX.
- Financing costs.

The cost of PT and ST plants with thermal energy storage is generally between $ 5000 and $ 10500/kW as listed in Table (9). The current levelized cost of electricity (LCOE) from CSP technology are listed in table(10). The other cost data are represented in figures (21.a, b, c, d, e and f).

Table (9). *Capital Costs and key parameters of PT and ST Plant [3, 62-63].*

	Source	Heat transfer fluid	Solar multiple	Storage(hours)	Capacity factor (%)	Cost(2010 USD/kWe)
Parabolic trough	Turchi, 2010a	Synthetic oil	1.3	0	26	4 600
	Hinkley, 2011	Synthetic oil	1.3	0	23	7 144
	Turchi, 2010a	Synthetic oil	2	6	41	8 000
	Turchi, 2010b	Synthetic oil	2	6.3	47-48	8 950-9 810
	Hinkley, 2011	Synthetic oil	2	6	43	7 732
	Fichtner, 2010	Molten salt	2.8	4.5	50.7	3800
			2.5	9	56	7 550
			3	13.4	67	9 140
Solar tower	Ernst and Young/ Fraunhofer, 2011	Molten salt		7.5		7 280
	Turchi, 2010	Molten salt	1.8	6	43	6 300
	Kolb, 2011	Molten salt	2.1	9	48	7 427
	Hinkley, 2010	Molten salt	1.8	6	41	7 463
	Fichtner, 2010	Molten salt	2	9	54	7 720
			3	12	68	9 060
			3	15	79	10 520

Table(10). *Low and high LCOE figures for PTC & ST [3,62-63]*

CSP type and source	2011		2012		Notes
	Low estimate	High estimate	Low estimate	High estimate	
			($/kWh)		
Parabolic trough					
IEA, 2010	0.20	0.295	0.10	0.14	Large plant, 10% discount rate
Fichtner, 2010	0.22	0.24			Proposed plant in South Africa. 8% discount rate. Lower end is for 100 MW plant with storage
	0.33	0.36			LCOE for India, lower value is for wet-cooled and higher value for dry-cooled
	0.22	0.23			LCOE for Morocco, lower value is for wet-cooled and higher value for dry-cooled
Based on Kutscher, et al., 2010	0.22		0.10	0.11	Data for the United States, adjusted to exclude impact of tax credits
Hinkley, et al., 2011	0.21		0.13		Data for a 100 MW plant in Queensland, Australia. 7% discount rate.
Solar Tower					
Fichtner, 2010	0.185	0.202			Proposed plant in South Africa. 8% discount rate. Lower end is for 100 MW plant with storage
	0.27	0.28			LCOE for India, lower value is for wet-cooled and higher value for dry-cooled
	0.22	0.23			LCOE for Morocco, lower value is for wet-cooled and higher value for dry-cooled
Kolb, et al., 2010	0.16	0.17	0.08	0.09	Data for the United States, adjusted to exclude impact of tax credits
Hinkley, et al., 2011	0.21		0.16		Data for a 100 MW plant in Queensland, Australia. 7% discount rate.
Parabolic trough and solar towers					
A.T. Kearney, 2010	0.23	0.32	0.13	0.16	

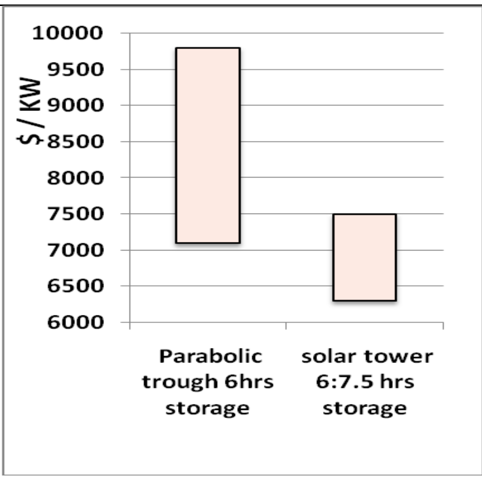

Fig.(21.a):Installation cost for different CSP technologies

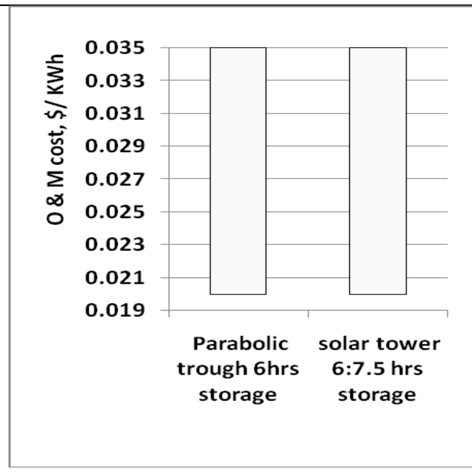

Fig.(21.d):O&M costs for different CSP technologies

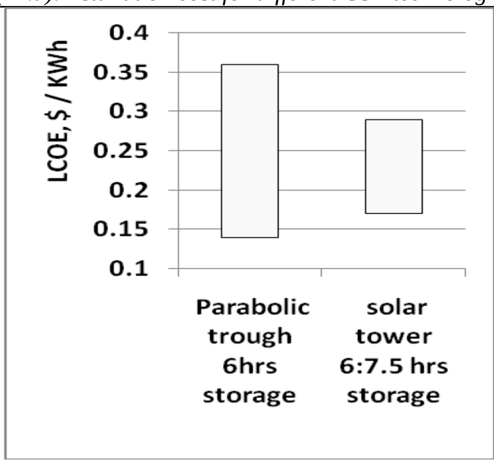

Fig.(21.b):Life cost of Electricity for different CSP technologies

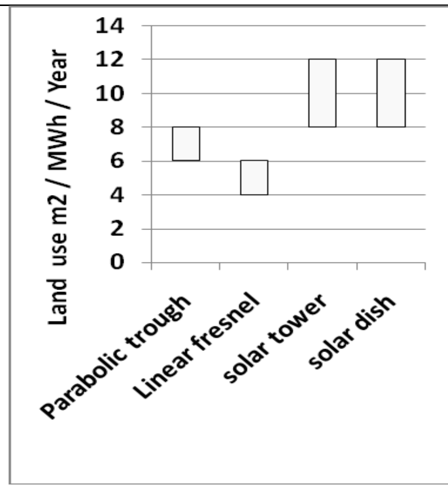

Fig.(21.e):Land use for different CSP technologies

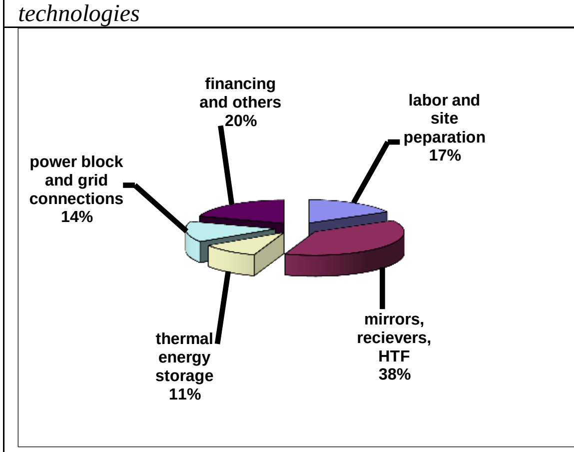

Fig.(21.c):Cost distribution of a parabolic trough power plant, 50 MW

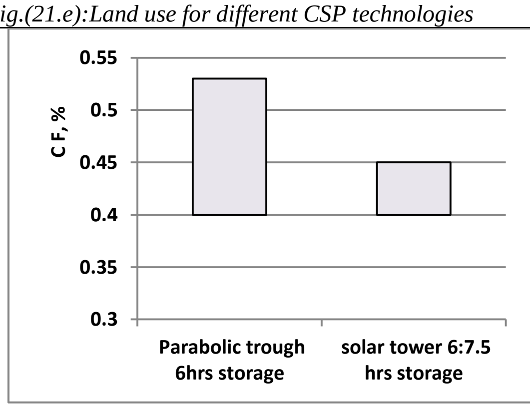

Fig.(21.f):Capacity factor Cost breakdown of a parabolic trough power plant, 50 MW

12. Conclusion

From the present study, it is concluded that:

- MENA region has a great potential for renewable energy and CSP is the future economic potential for electricity generation in MENA region.
- Governments of Developing countries have to realize, encourage and apply incentives for deployment of CSP projects. This can be

achieved through investment and researches.

- To produce power from solar heat energy, high temperature is needed, so concentration of incoming solar radiation is necessary using solar concentrators. Radiation needs to be focused onto a small target. So, concentrator optics and orientation needs to be accurate.
- Only beam radiation can be concentrated. Solar tracking is necessary (small cos θ).
- Concentration ratio (C) =60-100 can give up to 400 C, while C ≥ 200 can give temperature of 600-1000 ^{0}C.
- Concentration ratio is 25:100, 70:80, 300:1000, 1000-3000 for PT, ST, LF and Dish Stirling respectively.
- For PT, the ideal solar concentration ratio, $C_{ideal,2D} = \frac{1}{sin\theta}$

  Where 2D denotes to two dimensional (i.e PT collector).
- . Taking sun's angular width = 32' (0.5333 deg/2=θ.). Then $C_{ideal,2D}$ = 214. If higher $C_{ideal,2D}$ is required, a secondary mirror may be necessary.
- Yearly efficiency is 15: 25% for power generation from CSP power plants.
- Using heat storage, 5:7 hrs more operational time per day can be achieved.
- Land area requirement: based on generation weighted are 4:6, 6:8, 8:12, 8:12 m^2/MWh/year for LF, PT, ST and Dish Stirling respectively.
- CSP plants are capital intensive, but have zero fuel costs. PT plant without TES has capital costs as low as $4600/KW, but low capacity factors of 0.2: 0.25. Adding of 6 hours of TES increases capital costs to $7100: 9800/kW, but the capacity factors will be doubled.
- For ST plants, capital costs are $6300, 10500/kW when TES is 6 and 15 hrs respectively. The corresponding capacity factors are 0.4 and 0.8 respectively.
- For CSP plants, O&M costs are $0.02:0.035/kWh, which is relatively considered high.
- The LCOE is mainly depending on capital costs and the local solar resource. For instance, for a given CSP plant, the LCOE will be around one quarter lower for a DNI of 2700KWh/m^2/year than for a site with 2100 kWh/m^2/year.
- For CSP plants, the LCOE is currently high. Today, the LCOE is $0.2:0.36/kWh and $0.17:0.29 kWh for PT and ST plants respectively (at 10% cost of capitals). However for areas with excellent solar resources [MENA regions), it could be as low as $0.14:0.18$/kWh.
- Potential for Cost reduction is possible. For instance, for 1.9 GW of installed capacity, by year 2015, the LCOE will decline to $0.18:0.32/kWh and $0.15: 0.24/kWh for PT and ST plants respectively.
- ST plants might become the choice in future. Because it can achieve a very high temperatures with manageable losses using molten salt as a heat transfer fluid.
- Typical capacity is 10:300, 10:200, 10:200 and 0.01:0.025 MW for PT, ST, LF and Dish Stirling respectively.
- Operating temperature is 350:550, 250:565, 390, 550:750 ^{0}C for PT, ST, LF and Dish Stirling respectively.
- Plant peak efficiency is 14:20, 23:35, 18 and 30% for PT, ST, LF and Dish Stirling respectively.
- Annual solar to electric efficiency (net) is 11:16%, 7:20%, 13%, 12:25% for PT, ST, LF and Dish Stirling respectively.
- Annual capacity factor is 29:43(7h TES), 55(10h TES), 22:24, 25:28% for PT, ST, LF and Dish Stirling respectively.
- Collector concentration is 70-80, >1000, >60, >1300 suns for PT, ST, LF and Dish Stirling respectively.
- Steam conditions (T in C^o and P in bar) are (380:540 ^{o}C)/100 bar, 540/100 to 160:260/50, N/A for PT, ST, LF and Dish Stirling respectively.
- Water requirement in m^3/ MW of plant capacity is given below

PT plant	ST plant	LF plant	Dish-Stirling
3(wet cooling) 0.3(dry cooling)	2-3(wet cooling) 0.25(dry cooling)	3(wet cooling) 0.2(dry cooling)	0.05-0.1 (mirror washing)

- Labor represents 17% of the project cost and is an area where local resources can help to reduce costs in developing countries. Based on experience with Andasol 1, the site improvements, installation of the plant components and completion of the plant will require manpower of around 500 people.
- The most promising components that could be locally manufactured or provided by developing

countries are support structures, mirrors and receivers.

- Effect of orientation for 1-axis tracking:
- The performance of concentrated solar collectors (CSCs) depends on their orientation. Comparing north-south against east-west oriented collectors; it will have higher output over the year (roughly 5: 8%). While east-west oriented collectors have longer operating hours and therefore higher output in winter times.

Nomenclature

CAPEX	Capital Expenditure
DNI	Direct normal insolation, kwh/m^2
HVAC	Heating, ventilating and air conditioning
PT	Parabolic trough
S T	Solar tower
LCOE	Levelized cost of energy,$/kWhe
CSP	Concentrated solar power
MENA	Middle east and north Africa
MWht	Megawatt hour thermal power
MWhe	Megawatt hour electric power
TES	Thermal energy storage
Subscripts	
e	electric
t	thermal
Greek Symbols	
η	Efficiency

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