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A comparative Study on Photovoltaic and Concentrated Solar Thermal Power Plants

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Abstract - Recently solar energy receives a great attention as an important source of renewable energy. Solar energy is converted to electrical energy directly through photovoltaic (PV) or indirectly through concentrated solar power (CSP) system which converts solar energy to heat energy which in turn can be used by thermal power station to generate electricity.
This paper present a comparative study between the two types of solar power (PV&CSP). This study includes types, components, initial and running costs, efficiency, advantages, disadvantages and storage systems.

Key-words: Concentrating solar power plant, Photovoltaic, Renewable energy sources.

INTRODUCTION

The sun is the most plentiful energy source for the earth. All form of energy like wind, fossil fuel, hydro and biomass energy have their origins in sunlight. Solar energy falls on the surface of the earth at a rate of 120 pentawatts, this means all the solar energy received from the sun in one days can satisfied the whole world's demand for more than 20 years.
The potential of several renewable energy source based on today's technology is shown in Fig1. Future advances in technology will lead to higher potential for each energy source. However, the worldwide demand for energy is expected to keep increasing at 5 percent each year. Solar energy is the only choice that can satisfy such a huge and steadily increasing demand.

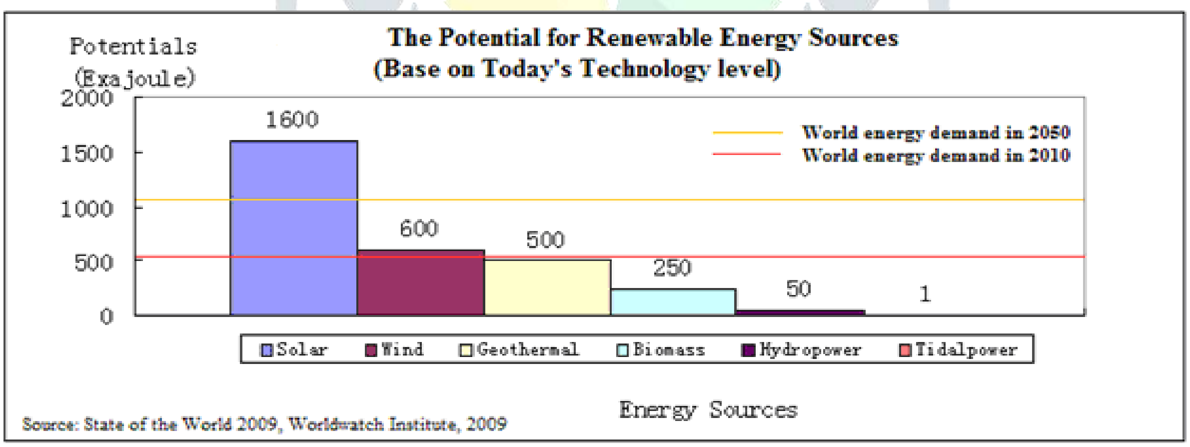

Figure 1: The Potential for Renewable Energy source

Renewable energy is the energy which comes from natural resources such as sunlight, wind, rain, tides and geothermal heat. These resources are renewable and can be naturally replenished. Therefore, for all practical purposes, these resources can be considered to be inexhaustible.
Among renewable energy source, solar technologies are capturing large interest. Most of the solar power systems in the market today can be divided into two major classes:-

- The direct solar power and
- The indirect solar power

The direct solar power refers to a system that converts solar radiation directly to electricity using a photovoltaic (PV) cell.
The indirect solar power refers to a system that converts the solar energy first to heat and after that to electrical energy,

as in the case of concentrated solar power (CSP). In a CSP plant, sunlight is focused on a heat exchanger; this heat is used to drive the turbine. The problems with these technologies are inefficiency and a very high capital cost. The typical efficiency of a CSP is about 15%. the highest efficiency of a silicon cell for example is 20%. On the other hand, Concentrating Solar Power (CSP) technology is now acquiring an increasing interest, especially if built with thermal energy storage.

PHOTOVOLTIC PLANTS (PV)

The PV plants can be categorized into two main typologies from the point of view of the installation mode:-

- stand alone and
- grid-connected.

The first one refers to PV plants which are not connected to the electrical grid of the local energy utility company. This typology of PV plants is usually used to feed small electrical load (e.g. for street lighting) or when the electrical grid is too far (e.g. an isolated rural house or a small offshore application). Stand-alone PV plants have a storage battery with stabilizer in order to guarantee that: **a**) the battery is not over-charged by the PV plant; **b**) the charge of the battery is not less than a prefixed threshold; **c**) the supply voltage is just that required from the electrical loads (if the electrical loads have to be fed by DC voltage) or from the DC side of the inverter (if the electrical loads have to be fed by AC voltage). Anyway, stand-alone PV plants are not used for high power.

The second one refers to the PV plants directly connected to the electrical grid of the local energy utility company. In this case, there is no battery because the electrical storage is represented just by the electrical grid. In fact, the energy produced by the PV plants and not simultaneously absorbed by the electrical loads is injected in the electrical grid; then, when the electrical loads require more energy than that produced by the PV plant, the lacking part is taken by the grid. Obviously, all the energy exchanges are regulated by commercial agreement. Nowadays, it is very common that PV plants are used to contribute to the total energy mix of a whole country or region; in this case the PV plant has high rated power, do not feed local electrical loads (except ancillary services of the PV plant as lighting) and injects all the produced energy in the electrical grid in order to balance the **global ratio (absorbed energy)/(produced energy)** of the whole electrical grid.
For the aims of this paper only this last typology of PV plants (high-power grid-connected PV plants) is important;
then the following sub-sections of this section regard only this specific typology of PV plants.

COMPONENTS AND OPERATION OF GRID-CONNECTED PV PLANTS

Figure 2 reports the scheme of a single part of a grid-connected multi-inverter PV plant. In fact the maximum rated power for a common photovoltaic inverter is 500 kWp, rarely 1MWp. Then, PV plants with rated power higher than 1 MWp have to be designed with some or many inverters which PV modules are connected to. The number of inverters depends on several factors: high partitioning guarantees the partial operation of the PV plant during its maintenance or when a fault has happened, but it implies higher initial investments as well as higher maintenance costs. Then, a large PV plant is constituted by several blocks as in Figure 2 and linked each other as explained in the following.

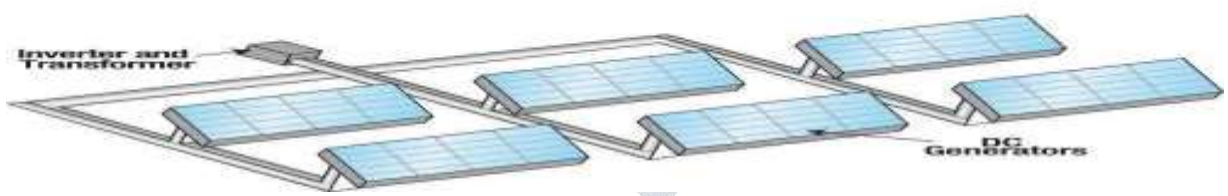

Figure 2 Single part of a multi inverter grid-connected PV plant

The main constitutive components of a grid-connected multi inverter PV plant are the following:

1. PV modules, which collect sun's rays and transform them in DC current.

2. Inverters, which convert the DC waveforms in AC waveforms.

3. Medium Voltage (MV) / Low Voltage (LV) Cabin, which raises the voltage level.

4. High Voltage (HV) / MV cabin which links the PV plant to the electrical grid. This last one is needed only for rated power higher than a prefixed threshold; for example, in Italy this threshold is 6 MWp. As in this paper we will compare PV plant and CSP plant with 40 MW of rated power, then it has to be considered.

Types	**Compound Parabolic**	**Paraboloid Reflector**	**V-Trough**	**Fresnel's Lense**
Construction	Made by two segments of parabolas	Use an anodized Al or simply a glass mirror which has a high reflectivity	Use arrays of trough shaped mirror	Made of several prisms arranged either linearly or in concentric circles
Concentration Ratio (CR)	$1/\sin\theta a$	$\pi r2/Acell$	$\sin[(2n+1)$ 灭 $+\theta]/\sin(\psi+\theta)$	$L.W/Acell$
Reflection of parallel ray into	Point	Point	Line	Point or Line
Tracking system	Not continuous tracking	Two axis	Not exist	Two axis

Table1. Comparison between different types of PV concentrators.

CHARACTERISTIC PARAMETERS OF THE PV PLANT

The layout of the PV plant for this paper is the following: twenty series-connected PV modules of 250Wp rated power constitute a single array. One hundred arrays are connected to the DC side of each 500- kWp inverter. Two inverters are linked to a 1MW LV/MV transformer in a single MV/LV cabin. Finally, eighty MV lines are collected in a single HV/MV cabin which allows to inject the AC electrical energy into the grid. Table 1 resumes the parameters of the PV plant.

PV Concentrators

Concentrating PV (CPV) systems use refractive lenses or reflective dishes to concentrate sunlight onto solar cells in order to make benefit of a higher concentration ratio (CR). There are many types of concentrators, the most known are:-

1) Compound Parabolic Concentrator (CPC)
2) Paraboloid Reflector.
3) V-Trough Concentrators
4) Fresnel’s Lenses

Four important parameters are taken into consideration in order to make the comparison between most important PV concentrators; these parameters are:

- Construction.
- Concentration ratio.
- Reflection.
- Tracking system

The comparison of the studied photovoltaic concentrators is given in Table 1. Based on the obtained results in this table, and depending on any project requirements, the PV concentrator can be selected.

Components of the PV Plant

The complete system of typical photovoltaic plant includes different components that should be selected taking into account the individual needs, site location, climate and expectations. The functional and operational requirements will determine which components the system will include major components such as :

1) ***PV Modules***, to convert sunlight instantly into DC electric power
2) ***Inverter***, to convert DC power into standard AC power.
3) ***Battery***, to store energy
4) ***Transformer***, to change the voltage in the installation for being able to connect with the distribution network. It is used a low voltage – medium voltage transformer.

5) ***Utility Meter:*** utility power is automatically provided at night and during the day when the demand exceeds the solar electric power production. The utility meter actually spins backwards when solar power production exceeds house demand, allowing you to credit any excess electricity against future utility bills.

6) ***Charge Controller***, to prevent battery overcharging.

LEVELISED COST OF ELECTRICITY GENERATION

The LCOE of renewable energy technologies varies by technology, country and project based on the renewable energy resource, capital and operating costs, and the efficiency / performance of the technology. The approach used in the analysis presented here is based on a discounted cash flow (DCF) analysis. This method of calculating the cost of renewable energy technologies is based on discounting financial flows (annual, quarterly or monthly) to a common basis, taking into consideration the time value of money. Given the capital intensive nature of most renewable power generation technologies and the fact fuel costs are low, or often zero, the weighted average cost of capital (WACC), often also referred to as the discount rate, used to evaluate the project has a critical impact on the LCOE.

There are many potential trade-offs to be considered when developing an LCOE modelling approach. The approach taken here is relatively simplistic, given the fact that the model needs to be applied to a wide range of technologies in different countries and regions. However, this has the additional advantage that the analysis is transparent and easy to understand. In addition, more detailed LCOE analysis results in a significantly higher overhead in terms of the granularity of assumption required. This often gives the impression of greater accuracy, but when it is not possible to robustly populate the model with assumptions, or to differentiate assumptions based formula used for calculating the LCOE of renewable energy technologies is:

$$\text{LCOE} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Where,

LCOE=The average lifetime levelised cost of electricity generation;

It = Investment expenditures in year **t** (including financing);

Mt = Operations and maintenance expenditures in year **t**; **Ft** = Fuel expenditures in year **t**;

Et = Electricity generation in year **t**; **r** = Discount rate;and

n = Life of the system.

Solar PV capital costs

The capital cost of a PV system is composed of the PV module cost and the Balance of System (BoS) cost. The cost of the PV module and the interconnected array of PVcells are determined by raw material costs, cell processing/manufacturing and module assembly costs. The BoS cost includes items such as the cost of the structural system (e.g. structural installation, racks, site preparation and other attachments), the electrical system costs include the inverter, transformer, wiring and other electrical installation costs) and the cost of the battery or other storage system. Prices for PV modules have fallen by between 30% and 41% in the year to September 2012 and by between 51% and 64% for the two years to September 2012, depending on the technology and source for European buyers.

Prices for PV systems in the United States have dropped by 50 percent or more in recent years, with the sharpest declines for large-scale projects.

Electrical Storage Systems (ESS)

The major categories of ESS used in PV plants are :

- Electro-mechanical electrical energy.
- Flywheel Energy Storage Systems (FESS).
- Electro-chemical energy.
- Battery Energy Storage Systems (BESS) there is a wide variety of battery technologies both in production and as topics of research.
- Lead Acid batteries.
- Capacitor and Super-Capacitor Storage Systems
- Electro-magnetic Superconductor Magnetic Energy Storage (SMES).

The Concentrating Solar Power Plant

Concentrating solar power (CSP) is a power generation technology that uses mirrors or lenses to concentrate the sun's rays, in most of today's CSP systems to heat a fluid and produce steam. The steam drives a turbine and generates power in the same way as conventional power plants.

CSP Technologies

CSP plants can be divided into two groups, based on whether the solar collectors concentrate the sun rays along a focal line or on a single focal point. Line-focusing systems include parabolic trough and linear Fresnel plants and have single-axis tracking systems. Point-focusing systems include solar dish systems and solar tower plants and include two-axis tracking systems to concentrate the power of the sun.

Components and Operation of the CSP Plant

This section focuses the attention on the CSP based on parabolic through. An Italian pilot project, based on this technology, has been realized by ENEL (Italy's largest power utility) and ENEA (Italian national agency for new technologies, energy and sustainable economic development) in the south of Italy, named Archimedes.

The CSP under investigation is constituted by the following main components:

- Linear parabolic trough-shaped mirrors to focus sun's rays onto a receiver pipe running along the focal line and containing a flowing fluid, named collectors;
- Hydraulic circuit with molten salts that connects the field of reflectors and the storage system, including the control system for controlling the temperature of the salts and the devices for loading and unloading of the salts;
- Pumping systems of the salts;
- Storage system made of two tanks with a circular section;
- Electrical power station equipped with two steam turbines (high and low pressure, respectively), a molten salt steam generator, a condenser with an appropriate cooling system (water or air) and the feed water preheating system.

The reflectors concentrates the sun's rays on the receiver and the heated fluid is transported to the energy conversion system. During this step a part of the fluid can be stored for a successive use. Then the remaining part is utilized to produce electrical energy. The energy conversion system is similar to a common fossil fuel plant utilizing a thermal steam Rankine cycle. Usually, a mineral oil is used but it is expensive and highly flammable, then it can lead to important problems if it leaks at the operating temperature (290°-390°C). For these reasons, it has been considered a fluid constituted by a mixture of salts, sodium and potassium nitrate; this fluid is largely used in the industry because chemically stable until 600°C and without corrosion problems. Moreover, the thermal storage allows to store the solar energy which can be used when the radiation is not present or limited (by night, in presence of clouds and so on). This is a very important task for each solar plant. In fact the unpredictability of the energy production is the main disadvantage of solar plants, which are usually used by the detractors of the solar energy plants. The thermal storage allows to decouple the collect of the thermal energy from the electrical energy production, i.e. it is not needed to produce and to use the electrical energy just when the thermal energy is collected. In this way it is possible to have a more efficient operation of the electrical generator eliminating the stops due to cloudiness and making the system more compatible with the demands of the electricity grid. Figure 3 reports a simplified scheme of the CSP. Three circuits are present:

- Primary loop, devoted to the harvesting, distribution and storage of the solar thermal energy;
- Secondary loop, where the thermal energy stored in the hot tank is utilized into the steam generator;
- Thermal cycle, where the thermal energy is transformed in the electrical one.

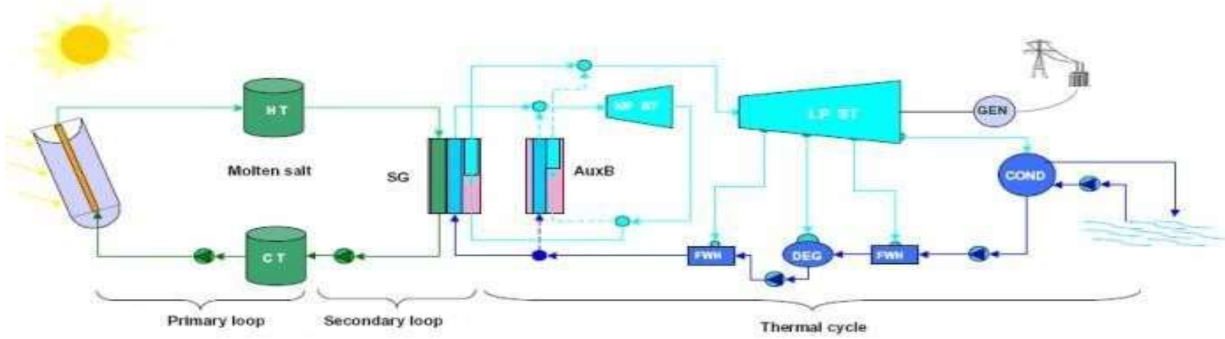

Figure 3: CSP under investigation

The operation principle of the CSP plant under investigation is the following. When direct solar radiation is present, the thermal fluid, taken from the cold tank at the temperature of 290°C, flows into the receivers and heats up until 550
°C. Then, it is pumped in the hot tank where it is stored. The flow capacity of the molten salts into the primary circuit is adjusted with respect to the solar radiation in order to maintain constant the input temperature of the hot tank. As the molten salts have high temperature of solidification (238°C), it is needed to maintain a minimum flow capacity when the solar radiation is not present or to provide heating systems of the pipes in order to avoid that the fluid temperature falls below it.

When electrical energy is requested, the salts stored into the hot tank are pumped into the heat exchanger, where the steam at high pressure and temperature is produced. Then, the molten salts are collected into the cold tank. As already said, the thermal cycle is similar to a common fossil fuel power station. Two turbines for high and low pressure are present, while the superheated steam has temperature of 525 °C and pressure of 120 bar when it expands through the high pressure turbine. The electrical rated power of the CSP is 40MW, while the efficiency of the thermal cycle is equal to 42.3%. An in depth analysis of the thermal performance of this CSP plant is reported in (VERGURA, DI FRONZO, 2012)

Cost Analysis of CSP

The cost of electricity generation from CSP is expected to decrease continuously. According to a study of renewable energy made by the IEA, the current CSP technology systems are implemented in the cost range of 0.19$/kWh to 0.25$/kWh. In the conventional power market, CSP competes with mid-load power in the range of 0.037$/kWh to 0.05$/kWh. As different scenarios have predicted, the costs of CSP can be reduced to competitive levels in the next 10 to 15 years. Competitiveness is affected not only by the cost of the technology itself, but also by potential price increases of fossil energy and by the internalization of associated social costs, such as carbon emissions. Therefore, it is assumed that in the medium to long term, competitiveness will be achieved at a level of 0.05$/kWh to 0.075$/kWh for dispatch able mid-load power. According to another report prepared by Electric Power Research Institute, when the global cumulative capacity of CSP implementation reaches 4GW,the cost of electricity generation from new plants in 2015 could be as low as 0.08$/kWh (nominal 2015dollars) or nearly 0.05$/kWh (real 2005 dollars).

Comparison between PV and CSP.

The PV and CSP are different in terms of technical aspects, but both techniques are essential clean energy alternatives to utilize solar power.

- PV converts sunlight directly into electricity (DC power) while CSP converts the light energy into thermal energy first, then use traditional turbine to convert heat into electricity (AC power).
- PV can use the solar diffuse radiation while CSP can only convert sun's direct radiation into power.
- Unlike PV's technique relies mostly on developing individual cell and module, the CSP technology relies heavily on the on-site constructing and final assembling and system integration.
- Energy storage of CSP is considerably lower than that of PV. With storage, power production can be shifted according to demand therefore is less dependent on the time period and daily weather conditions.
- The CSP technology is a still undeveloped industry, which is forced to face the competition and cost challenge come from the PV system.
- The Advantage of CSP over PV and many other renewable energy technologies is its ability to store the sun's energy as heat in molten salts, and to use it to generate electricity when the sun is no longer shining and at times when it may be most valuable to the grid. The molten salt heated by concentrating the sun's energy can be stored and kept hot for several hours. When electricity is needed, the heat stored in the salts can make the necessary steam. This storage lets CSP systems extend the "rush hours" of their generation patterns and generate electricity a few hours before the sun rises and a few hours after it sets, making it easier to integrate electricity from such plants into the grid.

- Cost comparison between PV versus CSP is presented in Table 2.

Scenario	Reference		Moderate		Advanced	
Year	Progress ratio	Investment cost	Progress ratio	Investment cost	Progress ratio	Investment cost
	(%)	(Euro/kW)	(%)	(Euro/kW)	(%)	(Euro/kW)
2005	0.90	4,000	0.90	4,000	0.90	4,000
2010	0.90	3,800	0.90	3,800	0.90	3,800
2015	0.90	3,400	0.92	3,230	0.86	3,060
2020	0.94	3,000	0.96	2,850	0.89	2,700
2030	0.96	2,800	0.98	2,660	0.91	2,520
2040	0.96	2,600	0.98	2,470	0.91	2,340
2050	0.08	2,400	1.00	2,280	0.93	2.160

Table 2: Cost Comparison – PV vs. CSP

CONCLUSION

Photovoltaic solar panels (PV) and concentrated solar power (CSP) are the most two commonly deployed technologies and are expected to have a rapid growth in both the short- and long-terms. Installations of CSP and PV electricity generation devices are growing rapidly. The PV share of electricity generation is greatly reduced as CSP is introduced into the model. This paper provided a brief summary for those who are interested in solar energy technologies and as a reference for those who want to invest or work in this field. PV and CSP technologies were discussed and reviewed their structure, performance, advantages and drawbacks. In addition, they have been evaluated and compared their mechanism, structure, and efficiency, along with other technical details. This study shows that PV systems present a noticeable cost reduction as compared with CSP systems. However, the effective energy storage offered by CSP systems make than relevant competitors to PV systems.

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