Comparative Study on Photovoltaic and Thermal Solar Energy Concentrators

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ABSTRACT

Renewable energy sources are non pollutant electricity production systems. Solar power is one of the most known renewable sources. The important goal in using solar energy systems is to reduce the production cost in order to compete with the other sources. This paper represents a study on solar power concentrators in their two conversion strategies: photovoltaic and thermal.

KEYWORDS

Energy production; Renewable energy; Solar power; Photovoltaic concentrators; Thermal concentrators.

1 INTRODUCTION

The need of energy in the world is increasing, especially because of the technology and the growth in the world’s population [1-6]. The total energy consumed in the form of coal, gas and oil, nuclear, hydro and renewable energy sources is known as primary energy [7-9]. This energy consumption was at 488.10^{18} Joules or 488 Exa-Joules (EJ) in 2005, it had grown from 385 EJ at over 2.4% of Compound Annual Growth Rate (CAGR) since 1995 (figure 1).

Searching for alternative energy sources became a necessity. Because of the limitation of fossil fuel’s quantity, renewable energy sources, used separately or in hybrid structure, are introduced to replace the pollutant non renewable energy [10-28]. Energy storage devices and systems for renewable and non renewable production energy are also treated in the literature [29-53].

Generally, there are three types of solar energy conversion: Photovoltaic (PV) Conversion which can be obtained by increasing the potential energy of the electron, Photochemical Conversion, and, Solar Thermal Conversion, which requires an increase in kinetic energy and heat generation (figure 2).

PV needs materials that have various energy levels separated from each other which can exist in semiconductor materials. Photovoltaic energy is one of the most interesting solutions, but it is still too expensive. However, its cost can be reduced significantly by using Luminescent Solar Concentrators (LSC). LSC can decrease the number of solar cells needed to produce an amount of energy by concentrating the light in a smaller area (figure 3). Using of multijunction cell increases the value of energy conversion efficiency from 20% to more than 30% [54].

In addition, the same principle of concentrating the light in a smaller area was used in thermal concentrators.

This paper discusses the solar energy concentrators in order to make the solar power competitive. It is divided in 6 Sections. Essential definitions are presented in Section 2. The most known PV concentrators are given and compared in Section 3. Different thermal concentrators are illustrated and compared in Section 4. The heat transfer fluid, storage techniques and cycles are also treated in this Section. Recent launched projects are given in Section 5. Finally, conclusions are discussed in Section 6.
2 SOME DEFINITIONS

The use of the concentrating collectors needs the definition of some terms as [56]:

2.1 Aperture Area ($A_a$)

It is their opened surface through which the incident solar flux is received.

2.2 Absorber Area ($A_{abs}$)

It is their total surface accepting the concentrated radiation.

2.3 Acceptance Angle ($2\theta_c$)

It is the limiting angle over which incident solar flux may deviate from the aperture area and still reach the absorber one. In order to track the sun, the moving process of the concentrators working with large acceptance angle is seasonally, while that of small acceptance angle is continuously.

2.4 Geometric Concentrating Ratio (CR)

It is the ratio of effective surface of the Aperture to that of the absorber. This value increases from 1 ("for a flat plate collector") to few thousand in some two-axis tracking systems ("for parabolic collector"):

$$CR = \frac{A_a}{A_{abs}}$$  \hspace{1cm} (1)

3 PHOTOVOLTAIC 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). Reflective surfaces are made by back-surface silvered low-iron glass which has a good durability, for lenses using acrylic plastic (PMWA) which has shown a very good weather-ability, some attempts to make lens from glass have been made but these ideas have still in laboratories [54]. PVC must be cleanable to remove dust and last at least 20 years. There are many types of concentrators, the most known are:

3.1 Compound Parabolic Concentrator (CPC)

The CPC is characterized by two segments of parabolas, AC and BD (figure 4). It consists of an entrance aperture, given by the segment CD, a reflecting side profile and an exit aperture [57]. The acceptance angle, which is 20, and the concentration of the solar radiation, which is at the exit aperture AB, determine the total length of a CPC. When the acceptance angle is reduced, the size of the concentrator will increase. This geometry offers a higher concentration ratio (CR), that is more than 10 suns [55]:

$$CR = \frac{A_{collect}}{A_{cell}} = \frac{1}{\sin \theta_a}$$  \hspace{1cm} (2)

It’s clear from this equation that a small acceptance angle, $\theta_a$, is needed for a more important CR. Rays parallel to the axis are reflected to the point called Point Focus Concentrator. This type of concentrators do not require continuous tracking because it is a non-imaging type of concentrator.
In addition, rays are not forced to be parallel or aligned with the axis. Compound parabolic concentrators are used to concentrate a solar energy collected by other type of collectors (heliostat or parabolic dish) to raise the concentration up to 40000. This operation is called "two stages concentrating devices" [58]. There is another type of concentrator that uses a single parabolic mirror which concentrates sunlight along a line; this type of concentrator is called Linear Parabolic Concentrator.

3.2 Paraboloid Reflector

This type of concentrator is used to concentrate solar power on a focus point (figure 5). The CR of such systems is very important because of the two-dimensional concentration; it can be more than 10000 suns [58].

\[
CR = \frac{A_{\text{collector}}}{A_{\text{cell}}} = \frac{\pi r^2}{A_{\text{cell}}} \quad (3)
\]

The reflector surface in the Paraboloid reflector is made using an anodized Al or simply a glass mirror which has a high reflectivity. This type of concentrators uses two axes tracking system.

3.3 V-Trough Concentrators

This type of concentrators is an important option to reduce the price of the PV electric power (figure 6). V-Trough concentrators are static. They do not require any tracking of the sun which reduces the cost of such system. The concentration ratio is near to 2 suns [59].

\[
CR = \frac{\sin[\pi(2n+1)\psi + \theta)]}{\sin[\pi(\psi + \theta)]} \quad (4)
\]

where \(n\) is the number of reflections, \(\theta\) is the acceptance angle and \(\psi\) is the trough angle.

3.4 Fresnel’s Lenses

Lenses are also used for concentrate the sunlight; the most known lenses used in concentrators are Fresnel’s lenses. Fresnel’s lenses are made of several prisms arranged either linearly or in concentric circles (figure 7) [55]. The conventional convex lenses are thicker and require more material than these lenses which are made from a polymer material. The concentration ratio of these lenses is high because of its large aperture area and short focal length.

\[
CR = \frac{A_{\text{lens}}}{A_{\text{cell}}} = \frac{L \cdot W}{A_{\text{cell}}} \quad (5)
\]

The Fresnel Lenses are also classified as "imaging" and "non-imaging" lenses. In case of imaging Fresnel lens, image of the sun is formed at the focal point, where as in case of non imaging form, sun’s image on the focal plane is a line along the axis of cylindrical parabolic reflector [60]. These lenses should be washed using small quantities of water. Using only Fresnel’s lenses might damage the solar cell if a small portion of the cell gets hot. The slight change of the light collection position due to the movement of the sun will adversely affect light-gathering efficiency [61].

3.5 Comparison between PV concentrators

The most important PV concentrators are previously presented. In order to make the comparison between them, four important parameters are taken into consideration, these parameters are:

- construction,
- concentration ratio,
- reflection,
- tracking system.

For these parameters, the comparison of the studied photovoltaic concentrators are given in Table 1. Based on the obtained results in this table, and depending on any project requirements, the PV concentrator can be selected.
4 THERMAL CONCENTRATORS

4.1 Types of Thermal Concentrators

A high light intensity will be focused onto a small area, by the use of mirror and lens systems. As a result of this concentration, the receiver absorbs energy from concentrator and transfers it to process being driven (engine, chemical reactor, etc). Electrical power is produced when the concentrated light is converted to heat in order to drive a turbine or motor engine for power generation. In general, there are four basic types of thermal concentrating solar power CSP systems: trough, tower, parabolic and Fresnel reflector.

4.1.1 CSP Trough

The CSP Trough uses curved mirrors. A single-axis or a dual-axis tracking system positions the mirror to retrieve the optimal amount of sunlight (figure 8). The concentration of sunlight is applied on thermally efficient receiver tubes that is positioned along the focal line of the trough. Sometimes a
transparent glass tube envelops the receiver tube to reduce heat loss. A fluid like synthetic oil, molten salt or steam circulates in the tubes absorbing the sun’s heat before passing through multiple heats exchange to produce steam [62]. The steam revolves around a conventional steam cycle turbine to generate electricity.

4.1.2 CSP Tower

Employs field of mirrors called "heliostats" that individually follow the sun on two axes, and reflect sunlight to a receiver at the top of a tower (figure 9). Early CSP tower systems generated steam directly in the receiver. This one collects the sun’s heat in a heat transfer fluid that flows through the receiver. Concentration is about 600-1000 times. The temperature of the fluid (steam, air, molten salt) that circulates in the tubes is 500-800°C. In this type, with a lower required salt inventory, the operating temperature is high compared to that in CSP trough. Its disadvantage is that each mirror must have its own dual-axis control.

4.1.3 Parabolic Dish or dish engines

It is an individual unit composed of solar concentrator, a receiver and an engine or generator. Multiple mirror facets are the basis in this concentrator that effectively track the sun on two axes, and reflect solar radiation towards a receiver (figure 10). The latter is set up an arm at the focal point of the reflectors and contains a motor-generator combination that operates using either a stirline engine or a small gas turbine [62]. Dish system is between 10 kW and 25 kW in size compared with other CSP technologies and can be placed on a varied terrain using small quantities of water. Even more dish conversion efficiencies are the highest reaching over 30% [62]. Its disadvantage is that the conversion from heat to electricity needs the moving of heavy engine, which requires a strong tracking system.

4.1.4 Linear fresnel reflector

Fresnel reflectors depend on flat or nearly flat mirror arrays to reflect sunlight onto elevated linear absorbers or receiver tubes. Water is the typical thermal that flows through the tubes and is converted into steam (Figure 11). Without the need for costly heat exchanger, steam can also be generated directly in the solar field. The advantage of this type is that the receiver doesn’t move with the mirror as in the CSP trough, so it doesn’t require rotating coupling between the receivers and the field header piping, thus providing additional design flexibility [62]. This type is cheaper than parabolic reflector, but it requires a mirror above the tube to refocus the missing rays or a multi-tube receiver that is large enough to capture missing rays without putting a mirror.

Figure 8. CSP Trough [62].

Figure 9. CSP Tower [58].

Figure 10. Parabolic Dish [58].
4.2 Heat Transfer Fluid (HTF)

There are many types of fluids that are used to transport heat in intention to produce electricity. The most important are: oil, molten salt and water.

4.2.1 Oil

Oil was the first HTF used, but it presents thermal instability problems [63]. 400°C is its highest temperature limit to work.

4.2.2 Molten salts

Molten salt is the economic option, has a high heat’s capacity and works with high temperature.

4.2.3 Water

Water is used as HTF with Direct Steam Generation (DSG). It is also used with lower costs and heat transfer losses as no heat exchanger system is required [63].

4.3 Storage

Solar thermal energy must be stored to produce electricity at night. The storage is used only in CSP tower and trough. There are multiple ways to store energy; the most important are:

4.3.1 Two-Tank Direct System

Same fluid used to collect heat and store it. The fluid is stored in two different tanks (figure 12): one for the high temperature and the second one for the low temperature. Fluid from the second tank launched to the receiver, its temperature becomes very high, and then it is stored in the high temperature tank to be flowed to the heat exchanger for generating steam, in order to produce electricity when needed later.

4.3.2 Two-Tank Indirect

Two-tank indirect systems work in the same way as two-tank direct systems, but there are two different fluids, one for the heat’s transfer and another for the storage [64].

4.3.3 Single-Tank Thermocline

In this type, there is a single tank which is used to store both the hot and the cold fluid in order to reduce the cost of a direct two-tank storage system (figure 13). The hot fluid is always on top in the thermocline storage [65], and the zone between hot and cold fluid is called "thermocline".
4.4 Cycle

Solar energy accomplishes a cycle depending on the type of concentrator. CSP tower executes Rankin cycle, but parabolic dish executes Stirline cycle.

4.4.1 Rankine Cycle

It is an idealized thermodynamic cycle of a heat engine that converts heats into mechanical work. There are four processes in the Rankine cycle [68]:

- Process 1-2: Raising the pressure of the fluid and giving little input energy to the pump.
- Process 2-3: Heating the liquid in the boiler at a constant pressure to become a dry saturated vapor.
- Process 3-4: Expanding dry saturated vapor through a turbine to generate power. The temperature and pressure of the vapor are decreased, and some condensation may occur.
- Process 4-1: Condensation of the wet vapor at a constant pressure to become a saturated liquid.

4.4.2 Stirline Cycle

The principle key of a stirline engine is that a fixed amount of a gas is sealed inside the engine. There are several properties of gasses that are critical to the operation of stirling engines:

- The raising of the temperature of a fixed amount of gas will increase the pressure,
- The compression of a fixed amount of gas will increase the temperature of that gas.

4.5 Comparison between thermal concentrators

Eight parameters are underlined for each discussed CSP system in order to compare it to the others. These parameters are: application, costs, axis, heat exchange, concentration type, receiver type, advantage and disadvantage.

The comparative study is given in Table 2. Based on this table and depending on the proposed project requirements, the best result of the CSP can be deduced.

<table>
<thead>
<tr>
<th>Types</th>
<th>Tower</th>
<th>Trough</th>
<th>Parabolic-Dish</th>
<th>Linear Fresnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uses</td>
<td>For large grid-connected power projects in the 30-200 MW size</td>
<td>For large grid-connected power projects in the 30-200 MW size</td>
<td>In single application or grouped in dish farms</td>
<td>Single application</td>
</tr>
<tr>
<td>Cost (USD/W)</td>
<td>2.5 - 4.4</td>
<td>2.7 - 4.0</td>
<td>1.3 - 12.6</td>
<td>No information</td>
</tr>
<tr>
<td>Axis</td>
<td>Dual</td>
<td>Single or dual</td>
<td>Dual</td>
<td>Dual</td>
</tr>
<tr>
<td>Heat exchange</td>
<td>Needed</td>
<td>Needed</td>
<td>No need</td>
<td>No need</td>
</tr>
<tr>
<td>Concentration on (in case of parallel rays)</td>
<td>Focal point</td>
<td>Focal line</td>
<td>Focal point</td>
<td>Focal line</td>
</tr>
<tr>
<td>Receiver</td>
<td>Mobile</td>
<td>Mobile</td>
<td>Mobile</td>
<td>Fixed</td>
</tr>
<tr>
<td>Advantage</td>
<td>With a lower required salt inventory the operating temperature is high compared to in CSP Trough</td>
<td>Concentrating sunlight to produce ice</td>
<td>Can be placed on a varied terrain using small quantities of water</td>
<td>Doesn’t require rotating coupling between the receivers and the field header piping thus providing additional design flexibility</td>
</tr>
<tr>
<td>Disadvantage</td>
<td>Each mirror must have its own dual-axis control</td>
<td>A transparent glass tube envelops the receiver tube to reduce heat loss</td>
<td>The conversion from heat to electricity needs the moving of heavy engine, which requires a strong tracking system</td>
<td>Requires a mirror above the tube to refocus the missing rays or a multi-tube receiver that is large enough to capture missing rays without putting a mirror</td>
</tr>
</tbody>
</table>
5 RECENT PROJECTS WITH CONCENTRATORS SOLAR POWER

There are lots of studies and projects launched to improve the quality of concentrators. The two most important studies concern the:

- **Miniature Concentrating PV on rooftops (MCPV):** Small systems which can be placed on rooftops can be more useful than far and big plants [69]. The MCPV is consists of a small parabolic dish, very easy to handle and doesn’t require special equipments. Solar thermal heating can also be used [70].
- **Super boost for CSP:** In the United States, and at the National Renewable Energy Laboratory, lots of research try to demonstrate that Super Critical CO2, which is a power cycle for CSP solar plants, is better than steam cycle. Its efficiency and performance are high at much lower temperatures than used with an air "Brayton cycle" as needed in steam cycle, that why, it's suitable for "power towers" and other applications. First of all, CO2 is compressed at high pressure, heated, then, used in solar receiver or heat exchange to get very high temperature and pressure, and then, expanded through the turbine [71].

6 CONCLUSION

Sun is a free and abundant source of energy, completely clean and non-polluting. Solar energy is the best choice for industrial applications amongst all renewable energies. This paper treats the case of PV and thermal CSP. There are some ways to make this power source cheaper to compete with other sources.

In PV concentrators systems, the expensive PV cell area is replaced by a cheaper optical material which reduces the material consumption. Also, the area of the solar cell is reduced by the factor of the concentration ratio which means the reduction of the cost of the solar cells and the cost of light conversion to electricity. In addition, the cell efficiency is increasing due to the concentration of light on cells.

For large grid-connected power projects in the 30-200 MW size, the use of tower and troughs is the best choice, whereas in order to have larger multi-megawatt projects, dish engine is used in single application or grouped in dish farms. Parabolic trough plants are the newest technology of solar energy, and most likely to be used for short-term deployments technology. High capacity factor is offered by CSP tower with its low cost and efficient thermal storage. Towers and dishes are better than parabolic trough plants with their high solar to electric efficiencies and low cost. Reducing the price of heliostats and the demonstration of the operability and maintainability of the molten salt technology are the best way to improve CSP tower. Dish engine systems need to develop at least one commercial engine and to decrease the cost of concentrator.

7 REFERENCES

57. Web site: http://share.pdfonline.com/7914cfae4f4b4305 97370514a63fe45/final%20project.htm  
61. Web site: www.isuzuglass.com/development/  
64. Mujica T.L., Net energy analysis of hybrid concentrated solar thermal power plants in Chilie: A selection methodology for optimal plant location based on sustainability attributes, Master Report, Faculty of Engineering, Pontificia Polytechnic University of Chile, (2009).
65. Web Site: http://www.eai.in/ref/global/ae/sol/csp/  
67. NREL Web Site: http://www.nrel.gov/csp/troughnet/thermal_energy_storage.html  