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Small scale concentrating solar plants for rural electrification

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ABSTRACT

Concentrating solar power (CSP) seems to be a promising solution for rural electrification in Sub-Saharan Africa. Small scale CSP plant appears to be most appropriate because it is suitable to the needs of rural communities: most of components can be found to be of low cost in the African market and there are available qualified local human resource to build the systems. A state of art of small scale CSP plants in the range of 1–500 kW_e are reviewed in this paper to showcase previous and current works undertaken throughout the world. 35 small scale CSP plants are identified and reviewed in the paper. Technical analysis is conducted on the identified plants to understand their operating principles. The technical analysis highlighted reasons behind the choices made for every component from the solar field to the power block.

1. Introduction

Energy is a basic need for every community; it represents both a driving force and an indication of development level [1,2]. With a national electrification rate of 32% in 2013 [3], sub-Saharan Africa is suffering from a lack of electricity access. According to the World Bank Group [4], more than 60% of sub-Saharan population live in rural areas for a mean electricity access rate lower than 17% [3]. As long as energy is a factor that contributes to development, expansion of local industries and increase of infrastructures cannot be achieved in rural areas without it. Therefore, socio-economic growth of sub-Saharan Africa is entirely slowed down by the delay of development of remote areas.

Sub-Saharan Africa has a huge and unused potential of renewable energy [5–7]. One of the solutions to increase rural electrification rate is the use of available renewable energy for power generation. Electricity based on renewable energy gives the advantage to reduce the dependency of sub-Saharan Africa on external resources (coal, gas, petroleum, etc.) for energy production.

Two solar energy decentralised systems are available for electricity generation: photovoltaic solar plants (PV) and concentrated solar power plant (CSP). In sub-Saharan Africa excluding South Africa, PV is a mature technology while CSP is unfamiliar.

The value of direct solar irradiation in sub-Saharan Africa, shows promising opportunities for electricity generation through CSP plants [8]. However, research conducted in developed countries using CSP plants indicates that these technologies are only affordable for high capacity installation. The scale effect, inducing the mass production of components will contribute to decrease the cost of electricity. Unfortunately, high capacity or large scale CSP plants are mostly of too large a capacity for the needs of rural populations and investments in these plants are very high for sub-Saharan countries. The development of small scale CSP plants are therefore need to be investigated in order to find possibilities of reducing the cost of electricity and meet the needs of rural areas.

2. Background – small scale CSP plant

The process of generating electricity with CSP plant is similar to those used by conventional thermal plants with only one difference: the heat source is not coal, gas, petroleum etc, but from the sun. Reflectors, usually mirrors, are used to concentrate sun rays and direct them onto a heat exchanger called solar receiver. The concentration of solar energy on the receiver provides high temperature environment; this thermal energy is collected by a heat transfer fluid (HTF) flowing through this receiver and used to feed a thermodynamic cycle directly or indirectly by flowing through storage tanks as illustrated in Fig. 1. Electricity is then generated through an alternator coupled with the turbine of the thermodynamic cycle [9].

Four types of concentrating systems are currently used in the world [10]. These are Parabolic Trough (PT), Linear Fresnel Receiver (LFR),

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Nomenclature

CHP	Combined heat and power
CRS	Central receiver system
CSP	Concentrated solar power
DS	Dish Stirling
DNI	Direct nominal irradiation
DSG	Direct steam generator
HTF	Heat transfer fluid
LFR	Linear Fresnel reflector
MSPT	Molten salt parabolic trough
ORC	Organic Rankine cycle
PT	Parabolic trough
WF	Working fluid

Dish Stirling (DS) and Central Receiver System (CRS); a graphic illustration of these technologies are given in Fig. 2.

Small scale CSP plant, by contrast to large scale CSP plant are designed to provide low range power at small scale. Basically, it is a low capacity electrical solar plant which can be standalone or connected to mini grid: it is then suited for the needs of small communities. According to the needs of rural communities in sub-Saharan Africa, this work focuses on small scale CSP plants defined as thermosolar plants providing at least power in the range of 1 kWe to 500 kWe.

3. Review on small scale concentrated solar power

Several studies have been conducted for the design and implementation of small scale CSP plants for rural and remote areas. During the past 40 years, several plants have been built and experimented in order to provide strong basis for the development and the deployment of the technology. In the following sections, a description of each of these plants is provided. Various efficiency parameters that relate thermal and electrical power, capitation area are defined as follow:

Thermal efficiency of the collecting system (1):

$$\eta_{th} = \frac{\phi_{HTF}}{\phi_{sol}} \tag{1}$$

Power-block efficiency (2):

$$\eta_{pb} = \frac{W_{pb}}{\phi_{HTF}} \tag{2}$$

Global efficiency (3):

$$\eta_{g} = \frac{W_{pb}}{\phi_{sol}} \tag{3}$$

where:

ϕ_{sol} is the incident solar flux received by the entire solar field
ϕ_{HTF} is the thermal power received by the HTF
W_{pb} is the mechanical power generated by the power-block

Systems described in this work are classified in two groups: linear (PT and LFR) and point-focus (CRS and DS) receiver systems. Under every type of technology, systems are described first, those that generate only power followed by those that are multi-generation systems.

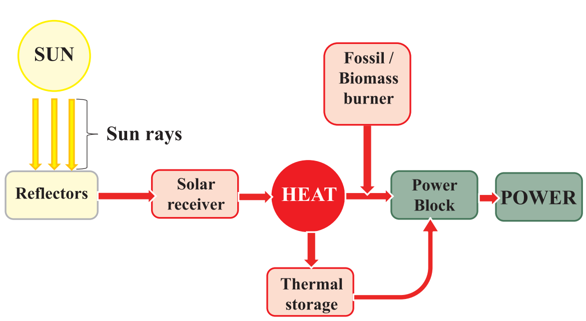

Fig. 1. Operating process of a concentrating solar plant.

3.1. Linear receiver systems

Table 1 highlights main parameters of small scale CSP plants based on linear receiver systems.

3.1.1. Parabolic trough technology

3.1.1.1. Small solar power systems (SSPS) parabolic trough [11]. The main objective of this project is the construction and operation of two demonstration CSP plants for power generation, one based on PT and the other on CRS. Each plant is expected to produce 500 kWe. The two CSP plants were built side by side in a city close to Almeria (Spain). The diagrams of the two systems are depicted in Fig. 3.[1]

The solar field of the PT system has a total collecting area of 7602 m^2 and is divided in three separate subfields with two different types of collectors. The first type of collectors is developed by the German company Man and the second by the American company Acurex. The collector from Man consisted of four parabolic troughs and has a two axis tracking system whereas the collector from Acurex is a single East-West axis tracking module. The first and third subfields used the collector from Man while the second subfield used the collector from Acurex. Synthetic hydrocarbon Santotherm 55 is used as HTF to feed the three subfields of the collecting area at 225 °C and flows out of the receiver at 295 °C to supply two storage tanks. Santotherm 55 is also used as storage medium. The first storage tank is common to the Man 1 and Acurex subfields; the tank was integrated with three diffusers and placed under a nitrogen atmosphere. The first tank can contain a minimum of 140 m^3 of thermal oil. The second storage tank is entirely connected to the Man 2 solar subfield. In addition to its 42 m^3 thermal oil, heat capacity of 358 t of cast iron was added in the second tank. The power block includes a steam generator, a steam turbine and an electric generator and uses water as working fluid; a maximal thermal efficiency of 19% is recorded for the power unit.

Results from experiments give sufficient basis to quantify the energy flows and losses linked to each part of the plant. Therefore, it helps in assessing the overall thermal efficiency of a day and a full year operation and performances of some key components. Experiments showed that at the design point, the thermal efficiency (8%) was lower than the estimated efficiency (12%).

It was finally stated that, SSPS project does not meet expectations set at its beginning. The overestimation of the solar irradiation, the low efficiencies of non-solar components, the thermal inertia of some elements and the high internal electricity consumption were the main reasons that impact the performance of these two plants. The system showed a global efficiency of 2.3%.

3.1.1.2. SEC plant [12]. From our knowledge, this plant, located at the Solar Energy Center (SEC) is the first CSP plant installed in India. It was built as a demonstration project for CSP field by Ministry of New and Renewable Energy. The plant consisted of parabolic troughs for a collecting area of 1250 m^2 and provides 50 kW_e. Hytherm 500 is used as HTF, the inlet/oulet temperatures in the receiver being respectively 200 °C and 300 °C. At the outlet of the receiver, thermocline storage of 14 m^3 capacity plays the back-up role where the HTF is also used as

[1] Reprinted from J Sol Energy Eng, 110, Wettermark G, Performance of the SSPS solar power plants at Almeria, 235–47, Copyright (1988), with permission from ASME.