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Solar thermodynamic plants for cogenerative industrial applications in southern Europe

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ABSTRACT

The paper deals with the preliminary design and optimization of cogenerative solar thermodynamic plants for industrial users. The considered plants are all based on proven parabolic trough technology, but different schemes have been analyzed: from a conventional configuration with indirect steam cycle and a heat transfer fluid such as synthetic oil or molten salts, to a more innovative arrangement with direct steam generation in the solar field. Thermodynamic parameters of the steam cycle have been optimized considering some constraints due to the heat requirements of the user, leading to a preliminary design of the main components of the system and an estimation of costs. Resulting net electric efficiency is about 10% for conventional synthetic oil plant, while 13% for innovative molten salts and DSG.

A comparison with conventional solar thermodynamic systems for electricity production and photovoltaic power plants shows the economic and energetic benefits of the cogenerative solution. Cost of electricity for solar plant is cheaper of about 20 €/MWh than conventional solar power application. Moreover, heat recovery allows to achieve a further 50% of CO_2 emission savings compared to reference solar plants for only electricity production.

1. Introduction

The role of renewable energies and, in particular, solar energy could be fundamental in future scenarios of worldwide increase of energy demand: solar energy can play an important role in country with high solar radiation. Focusing on electricity production from solar energy, photovoltaic and thermal systems are the available technologies. While photovoltaic seems to be a promising and appropriate technology for distributed generation, thermodynamic plants could be an attractive solution for centralized large-scale electricity production in the range of ten to hundreds of MW, with predictable low costs and relatively low land demand. Besides electricity generation, smaller-scale CSP thermal power plants could be appealing for cogenerative applications, producing heat for an industrial user the vicinity of the plant. In fact with a thermodynamic cycle a cogenerative system can be easily organized, potentially obtaining higher overall efficiencies than the full electric configuration.

This paper deals with the application of solar thermal energy as primary energy source in a cogenerative power plant for an industrial user characterized by two steam demands, each of 10 MW_{th}, at 12 and 4 bar respectively. The heat requests of the user are relatively constant: during the day the steam consumptions follow a quite flat profile. The plant is sized so as to cover the major heat demands, without considering any heat storage device, but simple assistance of an existing natural gas boiler. The plant is located in the South of Italy, in an industrial area surrounded by uncultivated and low cost grounds. The case can be representative of a typical mid-size industrial user, located in a country with high solar radiation.

The main component characterizing a solar thermal power plant is the collector, consisting of a concentrator that focuses the direct solar radiation on a receiver, so that plants are often referred to as ‘concentrated solar power’ systems (CSP). Generally speaking, depending on the type of concentrator, the solar power plants can be based on linear receivers (i.e. parabolic trough or Fresnel collectors), or point focus receivers, as solar towers or parabolic dish systems. Linear concentrators, mainly parabolic trough collectors, are currently the most proven solar thermal electric technology and are considered throughout this work.

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Nomenclature

A	Solar field Area [m^2]
c	Cost
CSP	Concentrated Solar Power
DSG	Direct Steam Generation
DNI	Direct Normal Irradiance [$W\ m^{-2}$]
G	Solar irradiance [$W\ m^{-2}$]
HCE	Heat Collection Element
HTF	Heat Transfer Fluid
IAM	Incidence Angle Modifier
OIL	Power plant with synthetic oil as Heat Transfer Fluid
RH	Reheater
SALTS	Power plant with molten salts as Heat Transfer Fluid
SEGS	Solar electric generating systems
SH	Superheater
ΔT	Temperature difference [°C]

Subscript

amb	ambient
ap	approach point
coll	collectors
dir	direct
el	electric
PC	power cycle
pp	pinch point
SF	solar field
th	thermal

2. State of the art

Parabolic trough systems are based on trough-shaped mirrors that reflect and focus the solar direct beam radiation on a linear receiver located at the focus of the parabola. The linear receiver, usually named "Heat Collection Element (HCE)", consists of a steel tube with a selective coating, for increasing absorptivity within the solar spectrum and reducing emissivity at higher wavelengths, surrounded by a glass tube with a vacuum annulus. The vacuum is required both to protect the selective surface from oxidative processes and to significantly reduce convective heat transfer at high operating temperatures. It is preserved through 'getters', that are metallic substances able to absorb gas molecules permeated into the vacuum annulus during the plant operation. The glass cylinder has anti-reflective coating on external surface to limit reflective losses. A heat transfer fluid (HTF) circulates through the receiver tube increasing its temperature. The HTF, then, is used to generate high pressure superheated steam in a steam generator coupled with a conventional reheated steam turbine to produce electricity. Solar power plants can operate stand-alone with a thermal energy storage in order to increase their availability, alternatively they can be coupled with a back-up fossil fuelled boiler or integrated in conventional power stations.

The nine SEGS (Solar Electric Generating System) power plants, built in California by Luz International Limited from 1985 to 1991, represent the first commercial attempt to produce electricity using parabolic trough technology. These plants have an installed electric generating capacity from 14 to 80 MW, with a total installed power of 354 MW; their main characteristics are summarized in Table 1 [4]. In those years Luz produced three types of parabolic collector: LS-1 (1984), LS-2 (1985) and LS-3 (1989). The general trend was to build larger collectors with higher concentration ratio increasing fluid outlet temperatures and power plant production [1,2]. One of the aims of LS-3 was also to reduce investment costs. However, LS-3 doesn't have the same performance, high availability and ease of installation and maintenance typical of LS-2, reaching the same maximum temperature (390 °C) [3]. These power plants have a back-up fossil-fired boiler that can replace the solar input during the period of low solar radiation, for a maximum of 2% of the yearly generated energy, fixed by law.

After these first attempts, the next solar thermal power plant built after 15 years in the United States is "Nevada Solar One". This plant, with a nominal production capacity of 64 MW_{el} and an investment cost of $266 million [6] (4156 $/kW), has been running since June 2007. Located in Boulder City, Nevada, 40 km southeast of Las Vegas, it receives a direct normal irradiance (DNI) of about 2600 kWh/m^2y. The facility is similar to the SEGS power plants using synthetic oil as heat transfer fluid with 391 °C as maximum temperature. This thermal level allows the production of steam at 100 bar. The solar field has second generation Solargenix collectors, SGX-2, 100–150 m long and 5.77 m wide with an optical efficiency, defined as the solar radiation absorbed by the receiver divided by the total radiation reaching the concentrator, of 77% [7]. The total solar field area is 357 200 m^2 and the plant is equipped with a back-up fossil-fired steam generator [6].

Another recent example of solar thermal energy plant is located in Andalusia and is the Andasol project, that consists of a 50 MW_{el} generation plant, taking advantage of the best DNI resources in Spain (2200 kWh/m^2y) and good transport access for

Table 1
Features of existing plants [4,5].

Power plant		Beginning of operation	Net power output [MW_e]	Solar field Outlet Temperature [°C]	Solar Field Area [$10^3\ m^2$]	Steam cycle efficiency [%]	Collector	Investment Cost[a] ($/$kW_{el}$)
SEGS	I	1985	13.8	307	83	31.5	LS-1/2	4500
	II	1986	30	316	190	29.4	LS-1/2	4500
	III/IV	1987	30	349	230	30.6	LS-2	3400
	V	1988	30	349	250	30.6	LS-2	3400
	VI	1989	30	390	188	37.5	LS-2	3400
	VII	1989	30	390	194	37.5	LS-2/3	3400
	VIII	1990	80	390	464	37.6	LS-3	2875
	IX	1991	80	390	484	37.6	LS-3	2875
Nevada Solar One		2007	64	391	357	37.6	SGX-2	4156
Andasol		2008	50	390	510	38.0	SKAL-ET	6000 €/kW_{el}
Archimede ENEA		2010	5	550	30	–	ENEA	–

[a] Investment costs are in current value, without actualization.