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Optimization of an atmospheric air volumetric central receiver system: Impact of solar multiple, storage capacity and control strategy

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ABSTRACT

Portugal has a high potential for concentrated solar power and namely for atmospheric air volumetric central receiver systems (CRS). The solar multiple and storage capacity have a significant impact on the power plant levelized electricity cost (LEC) and their optimization and adequate control strategy can save significant capital for the investors. The optimized proposed volumetric central receiver system showed good performance and economical indicators.

For Faro conditions, the best 4 MW_e power plant configuration was obtained for a 1.25 solar multiple and a 2 h storage. Applying control strategy #1 (CS#1) the power plant LEC is 0.234 €/kWh with a capital investment (CAPEX) of € 22.3 million. The capital invested has an internal rate of return (IRR) of 9.8%, with a payback time of 14 years and a net present value (NPV) of € 7.9 million (considering an average annual inflation of 4%). In the case of better economical indicators, the power plant investment can have positive contours, with an NPV close to € 13 million (annual average inflation of 2%) and the payback shortened to 13 years.

1. Introduction

1.1. Local context

Currently there are four concentrating solar power technologies (CSPs) applied in commercial power plants: central receiver systems (CRSs), parabolic trough, linear Fresnel and dish-Stirling engine. The South of Portugal is one of the European regions with higher annual solar direct normal irradiation (DNI). With the objective of exploring this potential, Portuguese authorities launched a recent call for network integration [1] of several small-scale projects (up to 4 MW_e) with the objective of building a CSP cluster using four commercial different CSP technologies. The CRS winner project was a 4 MW_e atmospheric air volumetric CRS. This is one of the most promising CSP technologies; it uses a field of two-axis tracking mirrors (heliostats) to concentrate solar direct normal irradiation (DNI), with concentration factors above 1000, into a solar receiver, exchanging heat with a heat transfer fluid (HTF) that drives the power block with good operating performances [2]. CRS power plants can be sub-divided according to the HTF: steam, atmospheric air, pressurized air and molten salts. Comparing all HTFs, atmospheric air has advantages in terms of availability, cost and environmental impact. Atmospheric air can be heated in a volumetric receiver, using concentrated solar energy, to temperatures around 700 °C, generating steam at 480–540 °C and 35–140 bar in a heat recovery steam generator (HRSG), which feeds a steam turbine paired with an electricity generator [2]. The most common power cycle used in commercial CSP power plants is the Rankine cycle, but other cycles such as the organic Rankine cycle or Brayton cycle (in pressurized air receivers) can also be used. Typically, the storage device is used to guarantee the power generation stability and/or extend operation, storing heat for several hours, which can be loaded or unloaded by reversing the airflow with two axial blowers, Fig. 1. The state of the art of atmospheric air volumetric CRS is Jülich solar tower (solar multiple 1.2, storage capacity of 1 nominal hour and steam conditions of 27 bar and 485 °C) [3].

1.2. Solar multiple

Power plant design is carried out from downstream to upstream: starting with the licenced power definition, steam cycle, air cycle, receiver and solar field. External limitations, such as available

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Nomenclature

α	escalation factor
CAPEX	capital investment
$C_{E,W}$	cost of the reference equipment at reference size or capacity
$C_{E,Y}$	cost of equipment at the required size or capacity
C_{rf}	insurance and debt interest coefficient rate
CRS	central receiver system
CRS_SM#_#S_CS#	central receiver power plant with (# multiple) of solar multiple, (# equivalent hours) of storage capacity and applying control strategy (# CS)
CS	control strategy
CSP	concentrated solar power
DC	direct costs
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DNI	direct normal irradiation
DP	design point
EBSILON	Ebsilon Professional software
ECOSTAR	European concentrated solar thermal road-mapping
E_{gross}	gross generated electricity
E_{net}	net generated electricity
ES	energy stored
HFLCAL	Heliostat Field Layout CALculation
HRSG	heat recovery steam generator
HTF	heat transfer fluid
IC	indirect costs
IRR	internal rate of return
K_{fuel}	annual fuel costs
$K_{O\&M}$	annual operation and maintenance costs
kW_e	kilowatt electric
kW_{th}	kilowatt thermal
LEC	levelized electricity cost
MW_e	megawatt electric
NPV	net present value
Q_{DNI}	power intercepted by the solar field
Q_{Int}	receiver intercept power
Q_D	power dumping
Q_{PB}	power input to power block
Q_{Rec}	receiver output power
Q_S	power to/from storage
REN	Portuguese electricity network, managed by the company REN (Rede Eléctrica Nacional)
SM	solar multiple
S_{max}	storage maximum
TES	thermal energy storage
UPORTO	Universidade do Porto
X_W	size or capacity of the reference equipment
X_Y	size or capacity of the required equipment

land and topography, affect power plant design. These limitations must be respected in power plant design and optimization processes. Several factors affect this phase, e.g. the solar multiple, storage capacity and control strategy, influencing power plant performance and cost, and their optimization is essential to find the best power plant design. The solar multiple (SM) is the ratio between the thermal power generated by the collector system (solar field and receiver) at the design point (DP) and the thermal power required by the power block at nominal conditions, Equation (1).

$$SM_{DP} = \frac{Q_{Rec,DP}}{Q_{PB,DP}} \quad (1)$$

The solar multiple defines the solar field excess power above the nominal power necessary to run the power block and which, in most cases, is stored or otherwise wasted. In solar-only power plants the solar multiple is always greater than one, so the power block operation is not confined only to solar clear sky conditions. The increase in solar multiple also represents higher capital investment (CAPEX), larger solar field, land area and receiver costs. Also the increase of solar multiple represents an increase in the solar field intercept power, Fig. 2.

1.3. Thermal energy storage

The power plant with 1.75 solar multiple (SM1.75_7S, Fig. 2) collects more solar energy than the power plant with solar multiple of 1.25 (SM1.25_7S, Fig. 2) and, as a result, the period of power block full load operation is extended. This is only possible using thermal energy storage (TES); otherwise this energy is dumped. With TES it is possible to decouple the power generation from the solar resource. Electricity generation can occur without solar resource and/or on demand by the electricity network, Fig. 2. The storage unit confers this essential and unique dispatchability characteristic to CSP electricity generation. It is thus possible to adapt the electricity generation profile to the national electricity demand, decreasing the need of backup and stand-by power. The Portuguese

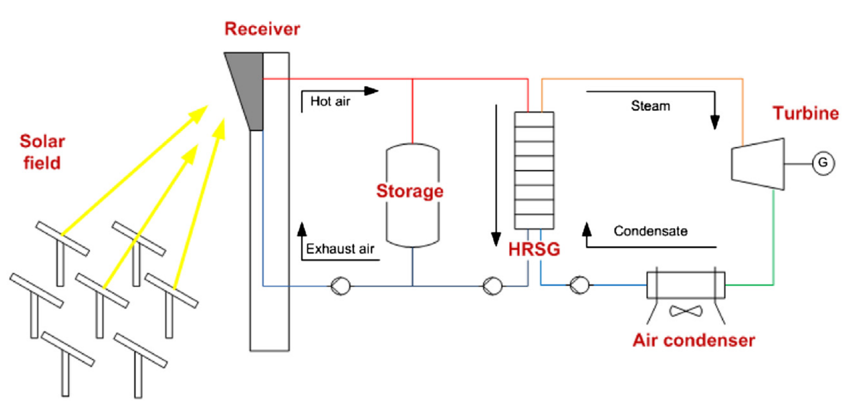

Fig. 1. Atmospheric air volumetric CRS schematic.