Energy Conversion and Management 174 (2018) 932–954

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Economical optimization of thermochemical storage in concentrated solar power plants via pre-scenarios

D. Salas[a], E. Tapachès[a], N. Mazet[a,b,*], D. Aussel[a,b]

[a] CNRS PROMES, UPR 8521, Rambla de la Thermodynamique, Tecnosud, F- 66100 Perpignan, France
[b] UPVD, Université de Perpignan Via Domitia, 52 Av. Paul Alduy, F-66860 Perpignan, France

ARTICLE INFO

Keywords:
Concentrated solar power plant
Thermochemical storage
SPOT market
Net Present Value
Black-box model
Optimal design

ABSTRACT

Thermal storage is a key point for the development of concentrated solar power technologies. This article aims to develop a methodology for the optimization, from an economic point of view, of a Concentrated Solar Power plant with thermal storage. It addresses two original aspects: (1) it incorporates a thermochemical storage process; (2) it considers the integration of the power plant's production in electricity SPOT markets that present strong price variations over the day, week, and seasons. The strategies of production defining the Storage/Storage-Production/Discharge phases must be optimized with regard to these variable prices. The relevant economic criteria is no more the usual Levelized Cost of Energy, but the Net Present Value, which considers also the revenues of the plant. The required optimization involves two sets of distinct variables which are optimized simultaneously: the physic variables of the thermochemical storage (defining its stored energy and its thermal power) and the operational/strategy variables, that define non-classic storage/production strategies adapted for the price curves. To take into account the time dependent feature of the problem, the notion of pre-scenarios is introduced, which allow to treat the problem, naturally formulated as an optimal control problem, under the classic setting of differentiable optimization. Under this scope, a solution for the optimal design problem of the plant is proposed. First results are presented for a Californian case. This first step highlights the improvement with respect to the classical production strategy (i.e. one storage discharge after sunset).

1. Introduction

The object of study of this article is a Concentrated Solar Power (CSP) plant integrating a thermochemical storage system. CSP plants have been largely studied in the literature and several plants are operational across the world [1]. Due to the evolution of electricity demand, the storage of energy has become fundamental for solar energy plants, in order to curtail and shift electricity production to match the demand. In addition, storage increases the value of CSP in electricity SPOT market, where price varies hourly.

The most implemented method of storage for CSP is based on the sensible heat of molten salts [1]. However, there exist two other alternatives: heat storage via latent heat of phase-change materials and thermochemical reactions. Pardo et al. [2] and Zhan et al. [3] published comprehensive reviews on these heat storage systems. Thermochemical processes are promising storage systems because of their high energy density and the wide range of operating temperature [4] but they have never been implemented experimentally in CSP plants.

Based on the knowledge and the know-how of PROMES-CNRS on the thermochemical processes for energy management (see, e.g., [5] where high temperature systems for heat and mass transfer are studied and optimized for solid/gas reactors, [6] where thermochemical solid/gas storage systems are studied for season operations in house heating, [7] where use of low-grade energy for cooling processes is studied and implemented, and [8] where endothermal/exothermal processes are studied for energy transportation) and on optimization techniques, this work proposes to evaluate the projects of CSP plants with thermochemical storage in the optimal design paradigm: loosely speaking, for a fixed electricity market, a fixed geographical location and a fixed expected life of the plant, the aim is to maximize the economical value of the plant. The main novelty of this approach is to optimize both the storage design (dimension and composition) and the dynamic operations of the plant (production/storage profiles) As a consequence the economical indicator that is maximized is the Net Present Value (NPV). Indeed, in this case the goal is both to minimize the cost of the plant (including the storage system) and maximize of the economic incomes since the optimization process chooses the discharge period according to the prices on the electricity market.

* Corresponding author at: CNRS PROMES, UPR 8521, Rambla de la Thermodynamique, Tecnosud, F- 66100 Perpignan, France.
E-mail address: mazet@univ-perp.fr (N. Mazet).

https://doi.org/10.1016/j.enconman.2018.08.079
Received 8 April 2018; Received in revised form 21 August 2018; Accepted 22 August 2018

Nomenclature

Latin symbols

ΔT_{eq}	gap temperature between T_c and T_{eq} [°C]
$\dot{m}_\alpha$	mass flow rate of the heat-transfer fluid at node n_α [kg/s]
BNI	Beam Normal Irradiance
c_{cw}	thermal capacity of the coolant (black cycle) [MW·s/(kg·K)]
c_{th}	thermal capacity of the heat-transfer fluid (red cycle) [MW·s/(kg·K)]
CSP	Concentrated Solar Power
DEC	energy density [kWh/m^3]
H	hours
$J(i,k)$	number of phases (depending on the subindex) in day k for the stage S_i
L	equivalent length of the reactor [m]
LCOE	Levelized Cost of Energy [€/MWh]
N	years of lifetime
n_α	node α of the plant design
N_{Days}	number of days of a stage
NPV	Net Present Value [€]
P_c	operational pressure of the reactor [bar]
Per_i	period i
q_1	thermal power used by the first thermal integration [MW]
q_2	effective thermal power dissipated in condensation process [MW]
q_3	thermal power dissipated during the cooling process of the Rankine cycle [MW]
q_D	average thermal power released by the reactor during Discharge phases [MW]
q_R	thermal power consumed by the Rankine cycle [MW]
q_S	average thermal power consumed by the reactor during Storage phases [MW]
q_u	useful power delivered by the solar field [MW]
q_{dis}	thermal power to be dissipated in condensation process [MW]
q_{dis}^u	fraction of q_{dis} recovered by the second thermal integration [MW]
q_{th}	thermal power from the solar field to the Rankine cycle [MW]
R_i	repetitions of S_i to complete period Per_i
r_{sw}	tube radius [m^2]
S_i	stage i
SM	Solar Multiple
t	time [h]
T_c	operational temperature of the reactor [°C]
T_α	temperature of the heat-transfer fluid at node n_α [°C]
T_{eq}	equilibrium temperature for the reversible reaction [°C]
t_{fin}	final time of one phase [h]
$t_{\mathrm{fin}}^{\mathrm{sol}}$	final time of the daylight interval [h]
t_{ini}	initial time of one phase [h]
$t_{\mathrm{ini}}^{\mathrm{sol}}$	initial time of the daylight interval [h]
T_{env}^d	average environment temperature during day [°C]
T_{env}^n	average environment temperature during night [°C]
USF	Uniform Series Factor
W_{elec}	electrical power injected to the market [MW]

Greek symbols

β	price factor for the estimation of the storage system's cost
ι_r	real discount rate
λ	price curve [€/MWh]
μ	operational variables of the reactor
ν	physical variables of the reactor
ρ_{eng}	apparent volumetric mass [kg/m^3]
τ	strategy variables

Indexes

α	number of the node in the plant design
D	discharge phase
i	period/stage
j	consecutive phase
k	day
P	Storage-Production phase
S	Storage phase

Up to the authors' knowledge, this is a new approach. In [9], Dowling et al. presented a comprehensive survey of techno-economical evaluation of CSP plants (with latent heat storage), where the importance of considering dynamical approaches for the design problem is announced. However, they also stated that, in the literature, the design of the plant is carried out following the LCOE indicator, while the NPV has been somehow reserved for models regarding the operation of the plant.

In fact, some recent works have investigated the optimization of production/storage profiles of CSP plants on SPOT markets and use the Levelized Cost of Energy (LCOE) or the total revenue as economical indicator (cost function). Wittmann et al. [10] uses a *dynamic programming* technique to determine the best production/storage profile in order to obtain the maximum revenue with up to a 48-h discrete time horizon. A similar work was carried out by Casati et al. [11]; they use also an Optimal Control technique to maximize the revenue of the power plant over a 1-month continuous time horizon. Finally, Channon and Eames [12] present a dynamic programming approach to adjust the operation of a fixed parabolic plant. Unlike this study, the aforementioned works fix the size the power plant, which is defined by three parameters: (1) the power block capacity, (2) the Solar Multiple for the solar field and (3) the energy storage capacity for molten-salt storage. Other authors have carried out similar studies concerning economical evaluation of storage systems, as for example, Guédez et al. [13] where economical value of CSP plants with storage systems is valuated using the LCOE in a electrical system with multiple renewable sources and where the incertitude is treated *via* scenarios, Thaker et al. [14] who perform a comparison between different technologies of storage systems based in discrete scenarios and cost models, and Bayon et al. [15] who compared different solid/gas thermochemical technologies with the classic molten salts technology for storage systems, using the LCOE as economic indicator. In these studies, the impact of the plant's operation is not taken into account.

The optimization of the combination of the storage design and the dynamic operation of the plant leads to a control problem. This control problem is here reformulated in a real-valued differentiable optimization model thanks to the concept of pre-scenario. The main reason to address the optimal design problem under this setting is that it is the robustest one concerning optimization. Both algorithms' theory and implementations have been widely developed, giving reliable results in fairly general cases. Due to the complexity and huge size of the optimal design problem of a CSP plant, it is necessary to model it in the most trustful setting available. For an introduction to differentiable optimization, see [16], and for an introduction in optimal control theory, see [17].

The work is organized as follows: the next section presents the general scheme of the CSP plant, and a short description of the assumed energy market model. Then, the economic criterion used in this work, namely, the NPV, and the optimization problem to be solved, are both