Applied Energy 121 (2014) 233–244

Contents lists available at ScienceDirect

Applied Energy

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

Uncertainty and global sensitivity analysis in the design of parabolic-trough direct steam generation plants for process heat applications

R. Silva [a,b,*], M. Pérez [a,b], M. Berenguel [b], L. Valenzuela [c], E. Zarza [c]

[a] CIESOL Research Centre for Solar Energy, UAL-CIEMAT Joint Centre, University of Almería, Ctra. Sacramento s/n, Almería 04120, Spain
[b] Automatic Control, Electronics and Robotics Research Group, University of Almería, Ctra. Sacramento s/n, Almería E-04120, Spain
[c] CIEMAT, Plataforma Solar de Almería, Ctra. Senés, km 4, E04200 Tabernas, Almería, Spain

HIGHLIGHTS

- Global sensitivity and uncertainty analysis of DSG for process heat is developed.
- Total sensitivity indices of design indicators are computed with the Sobol's method.
- The reliability of energy and economic performance variables is evaluated.
- For the case studied DSG modelling uncertainty is mitigated by economic uncertainty.

ARTICLE INFO

Article history:
Received 27 October 2013
Received in revised form 21 January 2014
Accepted 29 January 2014
Available online 3 March 2014

Keywords:
Parabolic-trough
Process heat
Direct steam generation
Uncertainty analysis
Total sensitivity indices
Sobol's method

ABSTRACT

A non-deterministic uncertainty and global sensitivity analysis, based on the Sobol's method, is developed for a parabolic-trough direct steam generation plant for process heat applications. The objective of this work is to evaluate the robustness of the simulation-based design stage, identifying major modelling sources of uncertainty, as well as quantifying and ranking the relevance of its contribution to the system performance output uncertainty. An important finding obtained from the case considered in this work is that, although the complex characteristics of the direct steam generation two-phase regime introduces additional sources of uncertainty into the low-level modelling stage, the propagation and impact of this uncertainty to system level energy and economic-based design indicators is largely mitigated by higher-level input factors uncertainty.

The economic design indicator uncertainty and global sensitivity analysis shows that the lowest relative output uncertainty is obtained by the levelized cost of energy with a coefficient of variation of 4.3%; followed by payback time with 12.1%. The largest contributors of input factors uncertainty to the levelized cost of energy uncertainty are the market discount rate and boiler efficiency, showing total sensitivity indices of 0.67 and 0.23, respectively.

1. Introduction

The increasing interest in solar industrial process heat is demonstrated by the growing number of recent studies in market potential [1–6], as well as by ongoing efforts to develop suitable collector technology to efficiently address that potential [7–11]. In the industrial sector, the most commonly used heat distribution medium is steam, due to its high energy density, simplicity to control and distribute, and the already extensive experience gained in its handling [12]. There are, at present, several available solar system configurations that can generate saturated steam at low pressure – the unfired boiler, indirect steam generation and direct steam generation systems [12]. These configurations have various relative advantages and drawbacks depending on the perspectives of the particular criteria, such as energy efficiency, integration simplicity, dispatchability, environmental issues, safety, and economic performance. Nonetheless, out of the options available, direct steam generation (DSG) is considered to be one of the most promising possibilities for lowering steam generation costs using solar systems. Previous scientific studies report that direct steam

* Corresponding author at: CIESOL Research Centre for Solar Energy, UAL-CIEMAT Joint Centre, University of Almería, Ctra. Sacramento s/n, Almería 04120, Spain. Tel.: +34 95001403.

E-mail address: ricardosilva@ual.es (R. Silva).

http://dx.doi.org/10.1016/j.apenergy.2014.01.095
0306-2619/

Nomenclature

A_c	collector aperture area, m^2
A_e	absorber tube external area, m^2
A_i	absorber tube internal area, m^2
b_1	incidence angle modifier coefficient, degree^{-1}
b_2	incidence angle modifier coefficient, degree^{-2}
C_e	cost of electricity, €/kW h
C_{et}	cost of electricity trend, %
C_f	cost of auxiliary fuel, €/kW h
C_{ft}	cost of auxiliary fuel trend, %
d	market discount rate, %
f	friction factor
G_b	direct solar irradiance, W/m^2
h_f	convection heat transfer coefficient, W/m^2 °C
h_L	convection heat transfer coefficient in liquid phase, W/m^2 °C
h_{TP}	convection heat transfer coefficient in two-phase, W/m^2 °C
f_{bs}	fraction of shaded area
k_e	end losses correction factor
k_θ	incidence angle modifier
Q_a	collector absorbed power, W
Q_L	collector thermal losses, W
Q_u	collector useful power, W
T_a	ambient temperature, °C
T_{ab}	absorber temperature, °C
T_f	fluid temperature, °C
U_L	global heat transfer coefficient, W/m^2 °C
U_L^0	coefficient of global heat transfer coefficient, W/m^2 °C
U_L^1	coefficient of global heat transfer coefficient, W/m^2 °C
η_o	optical efficiency of collector
η_b	boiler efficiency, %
η_p	pump efficiency, %
θ	incidence angle, degree
Φ^2	friction multiplier for pressure drop in two-phase stage
IAM	incidence angle modifier

Abbreviations

CSP	concentrated solar power
DAE	differential algebraic equations
DSG	direct steam generation
EOS	equations-of-state
FAST	Fourier amplitude sensitivity test
IAPWS	international association for the properties of water and steam
IEA	international energy agency
IST	industrial solar technology
LCOE	levelized cost of energy
LCS	life-cycle savings
MCR	maximum continuous rating
OAT	one-factor-at-a-time
PCC	partial correlation coefficients
PBT	payback time
PRCC	partial rank correlation coefficient
SRC	standardised regression coefficient
SRRC	standardised rank regression coefficient
TMY	typical meteorological year
TSI	total sensitivity indices

generation has the potential of lowering energy costs by up to 25% when compared to the more extended unfired boiler configuration [13]. These improvements are achieved by simplifying integration, an increase in solar field efficiency, fluid cost reductions and others – which translate into greater plant efficiency and lower capital costs. From a strictly thermodynamic point a view, integration with direct steam generation has the benefit of not requiring any additional temperature differential in the solar field outlet in order to overcome the unfired boiler pinch point, and hence has a lower outlet temperature and higher solar field efficiency. Moreover, its return piping can be directly connected to the pipe with lower condensate return temperatures, thus providing a lower return temperature than the unfired boiler configuration (which is restricted due to the heat exchanger thermodynamic integration between the solar and industrial plant). Another advantage is that the higher convection coefficient in the two-phase regime provides better heat transfer conditions between the fluid and the absorber tube, thus improving the collector's thermal efficiency.

Several solar collectors are currently capable of generating steam. However, according to the studies performed by [5,13,14], parabolic-trough collectors obtain the lowest energy costs for the medium temperature levels required by industrial processes. Recent studies of direct steam generation with small parabolic-trough collectors conducted by [15–17] assessed the influence of the main operational variables, identifying important design restrictions, as well as demonstrating the suitability of small parabolic-trough collectors for direct steam generation from a thermo-hydraulic perspective. At the experimental level, the works by [18,19] confirmed the technical feasibility of small parabolic troughs for integration to a steam consumption process. These recent milestones show that research in DSG is providing important contributions towards commercial introduction and a wider degree of industrial acceptance.

Nevertheless, the physical mechanism behind direct steam generation still places special challenges on solar energy engineers when compared to simpler one-phase systems; this is because of the more complex characteristics of two-phase flow regime modelling. For example, during the phase-change transition in the solar field, there is a pronounced thermo-hydraulic coupling between temperature and pressure. For this reason, the correct assessment of pressure losses becomes a more determinant factor in performance assessment – given that they not only affect hydraulic performance but indirectly affect thermal performance, as well. Added to this, there is a more prominent heat transfer coefficient difference from off-test conditions than in the liquid phase, leading to increasing relevance of the local flow regime and phase change conditions. Furthermore, in the two-phase regime, there is a strong coupling between pressure loss and local steam quality. Finally, correlations available in the scientific literature for two-phase regime modelling usually carry more uncertainty due to the higher complexity and multitude of physical phenomena involved.

In summary, all these factors may (or may not) induce relevant uncertainty in the model output since the impact of a specific input factors uncertainty is controlled not only by its deviation but also by the sensitivity of the model for that particular variable or parameter. Consequently, in order to explicitly assess and evaluate the relative importance of each input factor, a probabilistic non-deterministic approach along with a global sensitivity analysis is proposed in this work. The main objective is to provide additional information for the preliminary design stage of a solar industrial solar plant, as well as to help strengthen the validity and robustness of deterministic studies.