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Stochastic techno-economic assessment based on Monte Carlo simulation and the Response Surface Methodology: The case of an innovative linear Fresnel CSP (concentrated solar power) system

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ABSTRACT

Combining technological solutions with investment profitability is a critical aspect in designing both traditional and innovative renewable power plants. Often, the introduction of new advanced-design solutions, although technically interesting, does not generate adequate revenue to justify their utilization. In this study, an innovative methodology is developed that aims to satisfy both targets. On the one hand, considering all of the feasible plant configurations, it allows the analysis of the investment in a stochastic regime using the Monte Carlo method. On the other hand, the impact of every technical solution on the economic performance indicators can be measured by using regression meta-models built according to the theory of Response Surface Methodology. This approach enables the design of a plant configuration that generates the best economic return over the entire life cycle of the plant. This paper illustrates an application of the proposed methodology to the evaluation of design solutions using an innovative linear Fresnel Concentrated Solar Power system.

1. Introduction

This study is part of the FREeSUN[1] project, which is aimed at the design, optimization and construction of an innovative linear Fresnel CSP (concentrated solar power) system.

The specific mandate for this study consists of a step-by-step economic evaluation of the technical solutions proposed by the partners at every project phase. The evaluation must be performed in terms of the investment KPIs (key performance indicators), including the stochasticity affecting some of the system variables.

To achieve this goal, the authors created a dynamic and stochastic business plan which, by using the Monte Carlo method, analyses the behaviour of the primary economic variables related to the investment while varying specific technical and performance parameters.

Moreover, using the RSM (response surface methodology) technique, different design solutions are compared, considered both individually and in combination.

Consider, for example, two plant components A and B, each one with different possible alternatives ($A_1, A_2, \ldots, A_n$ and $B_1, B_2, \ldots, B_k$), as shown in Fig. 1.

The proposed approach, unlike typical deterministic analyses, leads to a regression model as follows:

List of abbreviations: CSP, Fresnel concentrated solar power; KPI, key performance indicators; RSM, response surface methodology; IRR, internal rate of return; NPV, net present value; PBP, payback period; DPBP, discounted payback period; LEC, levelized cost of energy; LCC, life cycle cost; MCM, Monte Carlo method; GCPVS, grid-connected photovoltaic system; SAPVS, stand-alone photovoltaic system; DNI, direct normal irradiance; DPR, discounted profitability ratio; ROI, return on investment; ROE, return on equity; PCR, project cover ratio; MSPE, mean square pure error; MSPE MED, MSPE of the mean; MSPE STDEV, MSPE of the standard deviation; ENEA, Italian National Agency for New Technologies, Energy and Sustainable Economic Development; pdf, probability density function; FCC, face-centred composite; ANOVA, analysis of variance; OFCF, cash flows; WACC, interest rate.

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[1] The FREeSUN project was born in 2009 under the competitive announcement “Industry 2015 – Energetic Efficiency” and financed by the Italian Ministry of Economic Development, for a total amount of 12.5 million Euros. The partnership, coordinated by Fabbrica Energie Rinnovabili (FERA), is composed of companies, universities and Italian research centers (CNR, Polytechnic of Milan, University of Genoa, University of Catania, and University of Florence).

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List of nomenclature

Net Present Value (NPV) is the algebraic sum of the cash flows over several years of the analysis horizon discounted at an interest rate
Pay Back Period (PBP) is the point of temporal equilibrium of the cash in and cash out discounted at an interest rate
Discounted Profitability Ratio (DPR) is the ratio between the net present value and the initial investment
Internal Rate of Return (IRR) is the interest rate at which the NPV is zero
Project Cover Ratio (PCR) is the ratio of the present value of the cash flows over the remaining full life of the project to the remaining debt in the period
Levelized Electricity Cost (LEC) is the price at which electricity must be generated from a specific source to break even over the lifetime of the project
Return on Investment (ROI) measures, per period, the rate of return on invested money
Key Performance Indicators (KPI) is a business metric used to evaluate factors that are crucial to the success of an organization
Response Surface Methodology (RSM) is a methodology that explores the relationships between several explanatory variables and one or more response variables

$$\widehat{y} = \varphi(A, B)$$

which is used to describe the behaviour of a single KPI varying the other components.

Therefore, the proposed approach identifies the solution A_iB_j that maximizes (or minimizes) the economic target KPI.

In this way, a techno-economic optimization of the plant is derived, in which all of the possible design decisions are made considering the economic return of the investment.

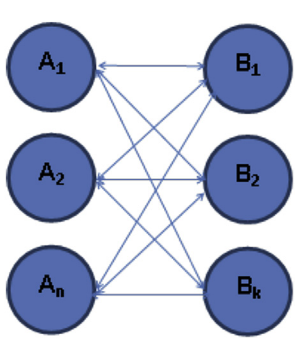

Fig. 1. Factor interaction scheme.

Furthermore, the presented methodology is generalized, and therefore applicable to any type of innovative plant design.

1.1. *Review of the literature*

To date, most techno-economic analyses applied to renewable power plants have focussed on the deterministic regime.

G.C. Bakos et al. performed a techno-economic study of an integrated solar combined-cycle power plant in Southern Greece. They determined the yearly cash flows of the investment, considering all of the connected direct and indirect costs, and calculated the primary financial indexes, such as the IRR (internal rate of return), the NPV (net present value) and the energy production cost. Finally, their paper presented a traditional sensitivity analysis on the effect of the contribution rate on the investment profitability [1].

M. Chandel et al. examined a solar photovoltaic power plant site at Jaipur (India) and determined the primary economic KPIs, such as the IRR, the NPV, the simple and discounted payback period (PBP (pay back period) and DPBP (discounted payback period)), and the LEC (levelized cost of energy) [2].

M. Horn et al. presented an investment evaluation, determining the NPV and the LEC of an integrated solar combined-cycle system in Egypt [3].

R. Hosseini et al. performed a comparative study of different traditional and solar power plants using the levelized electricity cost as the reference metric [4].

A comparison in terms of the LEC between linear Fresnel and parabolic trough collector power plants was performed by G. Morin et al. [5].

Comparative analyses using the LEC among different renewable electricity generation technologies have been developed by Varun et al. [6] and by S. Giuliano et al. [7].

A. Poullikkas has implemented a parametric study of different parabolic trough solar thermal technologies [8]. For this purpose, a simulation software package was used to analyse the investment in terms of the NPV, the IRR, the PBP and the LEC. The parameters considered included the plant capacity, the capital cost, the operating hours, the CO_2 ETS price and the annual land leasing.

W.T. Chong et al. performed a techno-economic analysis of an innovative wind–solar hybrid renewable energy generation system by applying the LCC (life cycle cost) method [9]. They considered the cash flows generated by the investment and calculated the NPV for the 25-year lifetime of the system.

D.L. Talavera et al. presented an investment analysis of PV systems located in buildings or public areas, including a sensitivity analysis of the NPV, the DPBP, the IRR and the LEC [10].

All of the studies mentioned above, while technically valid, provide evaluations that are not exhaustive given the stochasticity that characterizes many of the factors involved. The uncertainty connected to these variables has not been considered in the above-mentioned studies.

For this reason, recently, some researchers have begun to develop studies in the stochastic regime, considering, for some of the variables, probability distribution functions rather than deterministic values and using Monte Carlo simulations to determine the economic KPIs.

Falconett et al. have developed a probabilistic model to assess the effects of different governmental support mechanisms on the financial return (NPV) of small-scale hydroelectric, wind energy and solar PV systems. The model considers 17 random input variables, represented as probability distributions, such as the hours of sunshine, the wind regime, the installation cost, and the operating and the maintenance costs. The simulations were performed using Monte Carlo techniques [11].