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A comprehensive optimization model for flat solar collector coupled with a flat booster bottom reflector based on an exact finite length simulation model

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ABSTRACT

In this paper an original simulation and optimization model for flat solar collector coupled with a flat bottom reflector has been developed. The problem of simulation and optimization for such system is essential in order to find the proper configuration of the reflector able to obtain the expected maximum efficiency of the whole system. The proposed simulation model analytically determines the solar energy on the collector-reflector system and therefore the optimization model estimates the optimal values of the design parameters. A new comprehensive formulation of the shadowing and irradiating level on the collector, able to take into account the finite length geometry with variable dimensions, is presented. The number and the value of the angular positions, the time periods over which the angular positions should be adjusted, the size, the aspect ratio, between the length and the width of the reflector, and the overhangs are parameters treated simultaneously with a global optimization procedure. The model is integrated with an original scheme of optimization where energetic and economic aspects are both taken into account.

The simulations results of the study reveal the optimal number of angular adjustments per year, the existence of a small optimal neighborhood of the aspect ratio and the optimal size of the reflector, for which the maximum reduction of the payback time of the augmented system compared to its reference collector is achieved. The results presented in the study are related to the solar data of Italian latitude, but they can be easily extended for any geographical location.

1. Introduction

Nowadays assessing the optimal choice of an energy conversion system compared to others among the technologies widespread in the market, it is critical and requires specific analysis because it is played against marginal values of economic and energy competitiveness factors. The optimal choice is a result of a complex analysis in which besides the thermodynamic aspects, environmental and energy policies are also involved that dynamically promote some solutions compared to others.

In the light of these aspects the optimization of a system from an energy, economic, and environmental point of view needs to have specific analytical tools to assess the behavior of a conversion system among several different solutions. Accurate and efficient simulation and optimization models are particularly required in order to avoid a mistaken estimation of the profitability of the project.

In the current study a mathematical model for supporting the analysis and the design of the proper configuration of a flat solar collector coupled with a booster flat bottom reflector, is presented in detail.

The work is inspired by the fact that the overall performance of a conventional flat plate solar collectors can be significantly improved if an additional reflective surface is assembled in a proper configuration with the collector. The addition of a reflector offers profitable results that can be summarized in the following aspects:

(a) increases the total equivalent active uptake area or reduces the collector and ground area requirement [1];
(b) increases the useful temperature to match the working fluid temperature with those of the solar power generation plant [2,3]
(c) maximizes the energy production just during a selected specific

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Nomenclature

$\mathbf{A_c}$ absorber surface of the solar collector [m^2]
$\boldsymbol{A_{c-ns}}$ portion of the collector area exposed to the direct radiation (beam and circumsolar components), [m^2]
$\mathbf{A_i}$ anisotropy sky index of the circumsolar diffuse radiation
$\mathbf{A_r}$ reflective surface of the reflector, [m^2]
$\boldsymbol{A_{r\to c}} \cap \boldsymbol{A_c}$ portion of the collector area exposed to the reflected radiation, (beam and circumsolar components) [m^2]
C_c cost of the collector, [€]
C_r cost of the reflector system, [€]
$C_{u,c}$ cost of the collector per unit area of the collector, $\left[\frac{€}{m^2}\right]$
$C_{u,r}$ cost of the reflector per unit area of the reflector, $\left[\frac{€}{m^2}\right]$
$\boldsymbol{D_m}$ number of days of the m-th month
E_c yearly energy supplied by the single collector in its optimal angular position, $\left[\frac{kWh}{a}\right]$
$F_{c\to s}$ view factor from the collector to the sky surface
$F_{r\to s}$ view factor from the reflector to the sky surface
$F_{c\to r}$ view factor from the collector to the reflector surface
$F_{c\to g}$ view factor from the collector to the ground surface
$F_{r\to g}$ view factor from the reflector to the ground surface
$\boldsymbol{G_{sc}}$ extraterrestrial solar constant on a plane perpendicular to the solar ray, 1367 $\left[\frac{W}{m^2}\right]$
$\boldsymbol{I_{b,0}}$ beam solar irradiance on a horizontal surface, (direct component and instantaneous value), $\left[\frac{kW}{m^2}\right]$
$\boldsymbol{I_0}$ total solar irradiance on a horizontal surface (instantaneous value), $\left[\frac{kW}{m^2}\right]$
$\boldsymbol{I_{d,0}}$ diffuse solar irradiance on a horizontal surface (instantaneous value), $\left[\frac{kW}{m^2}\right]$
$\boldsymbol{I_{d,0,cs}}$ circumsolar component of the diffuse solar irradiance on the horizontal surface, $\left[\frac{kW}{m^2}\right]$
$\boldsymbol{I_{d,0,iso}}$ isotropic component of the diffuse solar irradiance on the horizontal surface, $\left[\frac{kW}{m^2}\right]$
$\boldsymbol{I_T}$ total solar irradiance on the sloped surface of the collector (instantaneous value), $\left[\frac{kW}{m^2}\right]$
$K_€$ remuneration rate involved in the energy delivered by the augmented collector reflector system, $\left[\frac{€}{kWh}\right]$
$\boldsymbol{k_i}$ jth optimal operating time periods of the reflector when it is inclined at $\hat{\boldsymbol{\beta}}_{r,i}$, month
$\boldsymbol{L_c}$ length of the collector, [m]
ℓ_r overhang of the reflector, [m]
$\boldsymbol{n}$ nth day of the year
n_{c+r} payback time of the augmented system, year
n_c payback time of the reference collector operating without reflector, year
$\boldsymbol{R_{bc}}$ ratio of beam radiation on tilted collector surface to that on horizontal surface
$\boldsymbol{R_{br}}$ ratio o $\hat{\boldsymbol{\beta}}_c$ f beam radiation on tilted reflector surface to that on horizontal surface
$\boldsymbol{W_c}$ width of the collector, [m]
$\boldsymbol{W_r}$ width of the reflector, [m]
$\boldsymbol{x_i}$ ith optimal operating time periods of the collector when it is inclined at $\hat{\boldsymbol{\beta}}_{c,i}$, month
$\boldsymbol{y_i}$ ith optimal operating time periods of the reference collector when it is inclined at $\hat{\boldsymbol{\beta}}_c$, month
$\boldsymbol{Z_c}$ length of the reflector shadow on the collector plane along the width $\mathbf{W_c}$ of the collector, [m]

Greek Symbol

$\boldsymbol{\alpha_s}$ solar altitude angle, degree
$\boldsymbol{\alpha_N}$ solar profile angle or apparent solar altitude, degree
α_{N0} profile angle between the horizontal plane and the line on the vertical plane joining the upper edge of the reflector with the top edge of the collector
α_{N1} profile angle of a direct solar radiation, $I_{i,\alpha_{N1}}$, such that the profile angle of its reflected specular radiation $I_{r,\alpha_{Nr}}$ is equal to α_{N0}
α_{N2} profile angle of a direct radiation, $I_{i,\alpha_{N2}}$, such that the profile angle of its reflected specular radiation $I_{r,\alpha_{Nr}}$ is equal to $-\beta_c$
$\hat{\boldsymbol{\beta}}_c$ tilt collector angle, collector operating with a reflector
$\hat{\boldsymbol{\beta}}_{c,i}$ ith value of the tilt collector angle operating with a reflector
$\hat{\boldsymbol{\beta}}_c$ tilt angle of the reference collector operating without reflector
$\hat{\boldsymbol{\beta}}_{c,i}$ ith value of the tilt collector angle operating without reflector
$\hat{\boldsymbol{\beta}}_r$ tilt reflector angle
$\hat{\boldsymbol{\beta}}_{r,j}$ jth value of the tilt reflector angle
$\boldsymbol{\gamma_{s,i} \equiv \gamma_s(I_{i,\alpha_{Ni}})}$ azimuth angle of the direct solar radiation, degree
$\boldsymbol{\gamma_{s,r} \equiv \gamma_s(I_{r,\alpha_{Nr}})}$ azimuth angle of the reflected solar radiation, degree
γ_{s0} azimuth angle of the sun when the beam radiation assumes the direction parallel to the line joining the upper corner of the reflector with the correspondent upper corner of the collector
γ_{s1} . azimuth angle correspondent to the one between the line joining the lower corner of the reflector and the projection on the horizontal plane of the upper corner of the collector and the north south direction
$\{\gamma_{s,\mathscr{f}} = \mathscr{f}(\alpha_{Ni}) \sim \alpha_{Ni} \leqslant \alpha_{N0}\}$ ray trace equation for marginal condition of the complete shadowing of the collector due to the reflector. The couple $\{\alpha_{Ni}, \mathscr{f}(\alpha_{Ni})\}$ represents the combinations of the profile and azimuth angles for which the projection of the direct solar ray passing through the upper corner of the reflector intercepts the line angled as γ_{s1} joining the lower corner of the reflector with the projection of the correspondent upper corner of the collector onto the horizontal plane
$\{\gamma_{s,\mathscr{g}} = \mathscr{g}(\alpha_{Ni}) \sim \alpha_{Ni} > \alpha_{N0}\}$ profile and azimuth angles for which the projection of the direct solar ray passing through the upper corner of the reflector intercepts the line angled as γ_{s2} joining the lower corner of the reflector with the projection of the farther upper corner of the collector on the horizontal plane
$\{\gamma_{s,\mathscr{h}} = \mathscr{h}(\alpha_{Ni}) \sim \alpha_{Ni} > \alpha_{N0}\}$ and $\{\gamma_{s,\mathscr{j}} = \mathscr{j}(\alpha_{Ni}) \sim \alpha_{Ni} > \alpha_{N0}\}$ profile and azimuth angles for which the projection of the direct solar ray passing through the upper corner of the reflector intercepts the projection of one of the two sides of the collector on the horizontal plane
$\boldsymbol{\gamma_c}$ solar collector azimuth angle, degree
δ solar declination angle
$\boldsymbol{\theta_z}$ zenith angle
$\boldsymbol{\theta_{bc}}$ angle of incidence on the collector surface
$\boldsymbol{\theta_{br}}$ angle of incidence on the reflector; surface
$\boldsymbol{\varrho_r}$ reflectance of the reflector
$\boldsymbol{\varrho_g}$ reflectance of the ground
$\boldsymbol{\tau_s(m,d)}$ sun set time of the d-th day of the m-th month
$\boldsymbol{\tau_r(m,d)}$ sun rise time of the d-th day of the m-th month
$\boldsymbol{(\tau\alpha)'}$ effective transmittance-absorptance product
$\boldsymbol{\phi}$ terrestrial latitude
$\boldsymbol{\omega}$ hour angle
[] an additional bar on the symbol of a specific variable always denotes a numerical assignment to that variable, therefore it should be considered constant

Subscripts

"0" stands for a quantity referred to the horizontal plane