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Energy payback time and life-cycle cost analysis of building integrated photovoltaic thermal system influenced by adverse effect of shadow

M. Tripathy[a,*], H. Joshi[b], S.K. Panda[b]

[a] Department of Electrical Engineering, Indian Institute of Technology (ISM) Dhanbad, India
[b] Department of Civil Engineering, Indian Institute of Technology (ISM) Dhanbad, Dhanbad 826004, India

HIGHLIGHTS

- Modified HDKR model for finding accurate insolation because of adverse shadow effect.
- Optimum tilt angle of BIPV module for maximum insolation.
- EPBT and LCA of BIPV thermal system with consideration of adverse shadow effect.

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Keywords:
Energy Payback time
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ABSTRACT

This article presents the Life-cycle Cost Analysis (LCCA) and Energy Payback Time (EPBT) of Building Integrated Photovoltaic (BIPV) thermal systems with reference to Indian weather conditions. The insolation and optimum tilt angle values are based on modified HDKR (*Hay*, *Davies*, *Klucher*, *Reindl*) model which accounts for hourly insolation considering shadow effect. Electrical and thermal performance of semi-transparent BIPV thermal system is evaluated for different mass flow rate of air through the duct with series combinations. EPBT and LCC of BIPV thermal systems are evaluated for three different orientations of PV modules i.e., optimum tilt angle, horizontal and vertical orientations by considering adverse effect of shadow. The cost of energy produced by the system ranges between 1.61 and 3.61 US$/kW h depending on the climatic conditions of the place and the EPBT of the system is found to be ranging between 7.30 years and 16.9 years which is lower than the expected service life (30 years) of the modules. Both LCCA and EPBT are increased because of shadow effect but these values are decreased due to air flow through the duct which is provided below the PV module. Thus, the BIPV thermal system is viable both financially and environmentally and this may be used as a major renewable energy source. A contour map of EPBT and LCA is presented for all state capital of India for BIPV thermal system oriented with optimum tilt angle.

1. Introduction

With the decrease in availability of fossil fuel and the massive carbon footprint of the traditional energy systems, recent years have seen a great amount of research resources allocated to research about non-traditional energy sources. The major non-traditional sources are wind, solar and biomass energy. The global renewable power capacity is estimated around 785 GW and about 30% of that is attributed to solar PV energy.

China is the largest solar power producing country with about 293 GW productions while India holds a sizeable portion of the world renewable energy production as shown in Fig. 1 [1]. In India, cumulative grid interactive renewable energy capacity (excluding large hydro) is 44.24 GW having 61% is constituted by wind and 19% by solar energy [2,3]. In recent years, India has seen great increase in the solar power extraction which is increased to two fold in just the past year and is expected to increase further [4]. With rapid advancement in solar thermal technology and PV materials, solar energy extraction is becoming more technologically, economically and environmentally viable. In BIPV systems, PV panels are used for replacing traditional construction materials and become a part of the building and generate solar energy as well. These have been observed to be a great way to harvest the solar energy through installation of PV units integrated with the building. These systems can be installed in a variety of ways. Tripathy et al. [5] reviewed extensively on BIPV products and their suitable applications as different components of the buildings i.e., flat roof,

* Corresponding author.
E-mail addresses: meetarani@ee.ism.ac.in (M. Tripathy), hj9@illinois.edu (H. Joshi), sarat@iitism.ac.in (S.K. Panda).

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Nomenclature

I_{ex}	hourly extraterrestrial radiation on a horizontal surface (kW h/m^2)
I_g	hourly global radiation on a horizontal surface (kW h/m^2)
I_{beam}	hourly beam/direct solar radiation on a horizontal surface (kW h/m^2)
$I_{diffuse}$	hourly diffuse solar radiation on a horizontal surface (kW h/m^2)
I_T	hourly total solar radiation on a tilted surface (kW h/m^2)
R_b	ratio of the average daily beam radiation on a tilted surface to that on a horizontal surface
K_{sc}	shading coefficient
A_{roof}	area of PV roof (m^2)
B	width of PV module (m)
L	length of PV module (m)
$I(t)$	insolation (W m^{-2})
H	heat transfer coefficient (W m^{-2} K^{-1})
M_{ar}	mass of air in room (kg)
m_a	mass flow rate of fluid (air) (kg/s)
C_a	specific heat of air (J kg^{-1} K^{-1})
V	velocity of air in surrounding (m/s)
V_d	velocity of air in the duct (m/s)
N_a	no. of air changes per hour
N	no. of PV rows
V	volume of room (m^3)
U_t	top heat loss coefficient (solar cell to ambient) (W m^{-2} K^{-1})
U_{tt}	over all heat transfer coefficient (W m^{-2} K^{-1})
h_a	heat transfer coefficient of the air flowing through the duct (W/m^2 K)
h_r	heat transfer coefficient for room air in (W/m^2 K)
h_{td}	heat transfer coefficient for tedlar (W m^{-2} K^{-1})
h_o	heat transfer coefficient for ambient air (W m^{-2} K^{-1})
h_{bd}	total heat loss capacity through building (W K^{-1})
D	thickness (m)
K	thermal conductivity (W m^{-1} K^{-1})
T	temperature (K)
E_{out}	electrical output (kW h)

Greek symbols

α_a	absorptivity
β_c	packing factor
τ	transmissivity
η	electrical efficiency
ρ	density (kg m^{-3})
ν	kinematic viscosity (m^{-2} s^{-1})
β	tilt angle
ϕ	latitude of the site
ω_s	mean sunset hour angle for the given month
δ	solar declination angle
ρ_g	surface albedo

Subscripts

a	air
c	solar cell
d	duct
g	glass
t	top
r	room
am	ambient
td	tedlar
tg	top glass
bs	back surface
bd	building

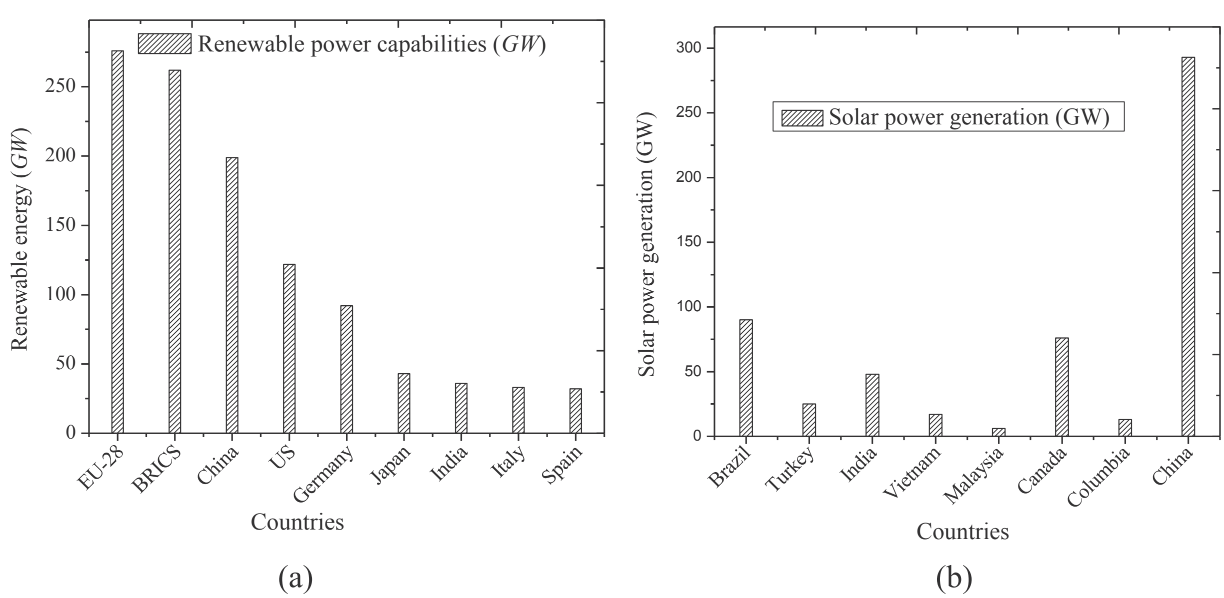

Fig. 1. (*a*). Renewable energy capacities of leading countries in GW, (*b*). Solar energy capacities of leading countries in GW. (Renewables 2016 Global Status Report.)

pitch roof, curved roof, façades, skylight, etc. Shukla et al. [6] reviewed on recent advancement in BIPV product technologies and introduced the best in class of the BIPV products and their properties along with international guidelines and testing standards.

The energy generation by BIPV system depends on solar irradiance and ambient temperature [7]. Orientation of BIPV systems is one of the key parameters for receiving maximum solar radiations. The performance of BIPV system is also highly influenced by the orientations of PV modules [8]. Many researchers [9–15] have established the relation between optimum tilt angle and latitude which are adopted by solar