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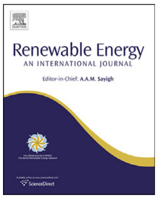

Review

Optimal design of photovoltaic energy collectors with mutual shading for pre-existing building roofs

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ABSTRACT

Technological advances in photovoltaic energy and reductions in the costs of photovoltaic (PV) cells make it likely that the roofs and faces of buildings will in the near future be clad with PV materials. These materials will act as insulation (passive efficiency), as a heat source (hot water) and as a source of electricity (active efficiency). This paper proposes a method for determining the most suitable orientation for the location of PV modules with a view to making optimal use of the solar irradiance available. The method can be extrapolated to all types of flat building shell, all orientations and slope angles, all geographical locations and all module sizes and performance efficiencies. It enables best-performing plant to be designed according to the needs of each user (maximum number of hours-equivalent or maximum output). The method is based on an algorithm that calculates the optimum tilt and azimuth angles of PV modules on the basis of estimated data for solar irradiance, PV module shading times and roof characteristics. The results are checked against the outputs of various PV installations currently up and running. This method is a highly useful tool for working towards building-integrated photovoltaic (BIPV) systems in urban settings.

1. Introduction

Numerous scientific papers have been written on how to calculate the optimum angle for positioning a PV module in different geographical locations and climates.

Those papers provide guidance for designers of PV and thermal solar power plants in calculating the efficiency and output of planned plants. However, most of the papers in question fail to consider a number of parameters that we believe are determinant in finding optimal solutions when PV modules are to be installed on pre-existing buildings [1–17].

Kristl et al. [1] proposes a tool for analysing the possibilities of various site layouts on a given location, especially in the early stages of design. It can be used for new developments as well as for new buildings which are going to be incorporated into the existing building tissue. Yang et al. [2] presents a mathematical model for calculating optimum tilt angles and azimuth angles, and is developed for the construction of buildings with integrated PV modules. Mutlu [3] proposes a model for obtaining the optimum slope of roofs fitted with PV panels. Sun et al. [4] researches the impact of building orientations, inclinations and wall utilisation fractions on the energy performance of shading-type elements. Strzalka [5] analyses PV implementation in urban environment, including installations on roof or facade surfaces with orientations that are not ideal for maximum energy production.

Jayanta [6] investigates the impact of PV orientation and inclination on annual, seasonal and monthly basis, on the following variables: incident insolation, PV output, PV efficiency, system efficiency, inverter efficiency and performance ratio (PR).

Mäki [7] demonstrates that partial shading of PV power generators has to be considered closely. Perpiñan [8] proposes a tool for studying shading at solar power plants: it quantifies the percentage of the surface area in shade depending on the gap between trackers and their tilt. Alonso-García [9] illustrates the effects that partial shading can cause in a PV array, and main conclusions of her work are addressed to emphasize the importance of reverse bias characterization of PV cells.

Most of the relevant body of literature on the matter comprises papers that seek to maximise PV module efficiency (kWh/kW) rather than to maximise output (kWh) from a roof or building face.

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Nomenclature

EPC	engineering, procurement and construction
LCOE	levelized cost of electricity (€/kW)
MC	module cost (€/kW)
PDIC	inverter, auxiliary installations, structure, construction and insurance cost (€/kW)
IIC	initial investment cost (€/kW)
C_t	cost per year (€/kW)
E_t	energy per year (kWh/kW)
r	discount rate (%)
FSOMC	full service operation and maintenance cost (€/kW)
HEP	households electricity price (€/kWh)
ESP	energy and supply price (€/kWh)
m	annual fixed cost of O&M related to electricity produced (%)
i	annual fixed insurance cost related to electricity generation (%)
T	lifetime of PV installation (years)
d	degradation rate (%)
ARIC	all risk insurance cost (€/kW)
IRR	internal rate of return (%)
CT	total cost of PV system (€/kW)
G_{pv}	total irradiance absorbed by the sloping surface (W/m^2)
G_{bh}	direct beam irradiance on a horizontal surface (W/m^2)
G_{dh}	diffuse irradiance on a horizontal surface (W/m^2)

θ_t	angle of incidence between beam and the sloping surface (°)
θ_h	angle of incidence between beam and the horizontal surface (°)
F_1, F_2	brightness coefficients
a, b	coefficients that depend on the angles of incidence
β	tilt angle of the surface (°)
ρ_g	albedo or reflection coefficient
n	day of the year
A_m	azimuth of modules (°)
$\mathrm{T_m}$	tilt of modules (°)
A_r	azimuth of roof (°)
T_r	tilt of roof (°)
I_{ph}	light-generated current (Amp)
I_0	dark saturation current (Amp)
R_s	series resistance (Ω)
R_{sh}	shunt resistance (Ω)
A	ideal factor
V_t	thermal voltage of the PV cell (Volt)
MPP	maximum power point
STC	standard test conditions
I_{mp}	maximum power point current (Amp)
V_{mp}	maximum power point voltage (Volt)
I_{sc}	short-circuit current (Amp)
V_{oc}	open-circuit voltage (Volt)
μ_{Isc}	temperature coefficient of short-circuit current (%/°C)
μ_{Voc}	temperature coefficient of open-circuit voltage (%/°C)

However, they leave aside financial issues such as whether the intention of the system installed is to cover the demand for electricity in the building itself. And technical issues such as whether the supporting structure designed for the modules is the lightest or cheapest possible option [2–5,7].

The method presented here enables designers to come up with a balanced solution adapted to the needs of each customer and each building where a plant is to be installed.

2. Technological & financial interest

The International Energy Agency [18] presents an assessment of the prospects for global energy markets for the period 2011–2035; the global energy demand increases by one-third from 2011 to 2035. However, as shown in Fig. 1, the share of fossil fuels in the world's energy mix falls from 82% to 76%. The share of renewable in primary energy use in this scenario rises from 13% in 2011 to 18% in 2035. Power generation from renewable energy increases by over 7000 TWh, meaning the half of the increase in total generation.

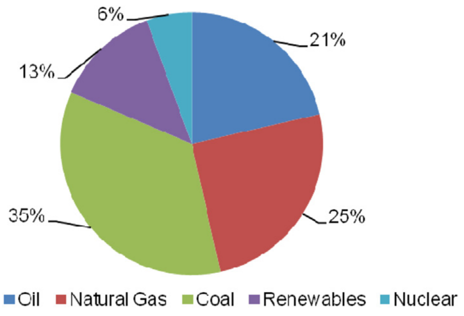

Fig. 1. World primary energy mix in 2011 [18].

Solar power has grown an average of 50% per year since 2005, reaching 100 TWh in 2012 [18]. In the New Policies Scenario, electricity produced from solar PV raises to 950 TWh in 2035. Solar PV on buildings accounts for the majority of installations; to that end, it is essential to reduce costs and increase efficiency, as well as minimising the area occupied.

Spain's renewable energy programme for 2011–2020 [19] “seeks to obtain a higher rate of penetration in buildings by using small and medium-power systems. On the contrary, it did not happen in the previous model, in which large-scale ground-level plants predominated. The systems installed close to the points of consumption, decrease the losses due to transportation and help to facilitate more sustainable development”. It forecasts that some renewable technologies could reach competitiveness under free-market (pool) conditions by 2016 and all would do so by 2030, while PV solar energy produced for self-consumption is now competitive, as presented in Fig. 2.

2.1. Economic analysis: methodology

Electricity generation by using PV solar energy leads to a dilemma, the choice of the most suitable system: fixed structures, mono-axis zenith trackers, mono-axis azimuth trackers, dual-axis trackers or polar-axis trackers.

In order to analyse the project rate of return (*IRR*), the key factor lies on the information needed for analysing a solar PV installation investment. This information can be divided into five general categories [20–22]:

a) Electricity cost (the electricity, both present and future): the electricity prices used in this paper are the average electricity prices for Households (*HEP*) (0.184 €/kWh) and the average electricity cost, -excluded Network costs and Carbon emissions prices (*ESP*) (0.075 €/kWh)-, for 2011 in the Union

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