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Performance analysis and economic assessment of different photovoltaic technologies based on experimental measurements

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ABSTRACT

The paper deals with extensive monitoring of photovoltaic technologies. It was carried out in the last 18 months at the outdoor development center HEnergia of HERA S.p.A. in Forlì (Italy). HEnergia has 8 different photovoltaic plants of small size (under 3 kWp) and they are differentiated by photovoltaic cell technologies (heterojunction with intrinsic thin layer, polycrystalline, cadmium telluride, amorphous silicon with microcrystalline silicon, silicon triple-junction cells, multi-junction Gallium Arsenide cells), by solar tracking systems (fixed installation, mono-axis or dual-axis tracker) and by optic devices (no concentration device, concentration through Fresnel lens or Cassegrain optic). Photovoltaic plants are remotely monitored and data on environmental conditions, module temperature and power production are continuously acquired and stored by a PC. Photovoltaic plant performance can thus be measured on-site and compared in relation to different environmental conditions. Moreover, the impact of maintenance activities (as for example the cleaning of photovoltaic modules) on photovoltaic plant performance is also assessed. On the basis of experimental data, the paper also shows an economic assessment of photovoltaic plants.

1. Introduction

The worldwide market for PhotoVoltaic (PV) systems has grown rapidly in the last few years [1], also thanks to specific national and transnational incentive programmes. As a consequence of this growth, the PV electricity generation cost continuously decreases. The opposite trend is shown by electricity prices for end-users and fossil fuel prices for thermal power plant operators. The intersections of PV electricity generation cost and electricity price or fossil fuel price are defined, respectively, as grid-parity and fuel-parity. When grid-parity or fuel-parity is reached, it means that PV plants are cost neutral. Different kinds of PV modules are available on the market, claiming both high performance and reliability, but commercial PV module specifications refer to Standard Test Condition (STC), thus being not representative of real environment conditions in which modules have to operate. Real performance analysis is fundamental to develop models and simulation tools used to predict energy production of PV modules and thus to make informed economic decisions. Various studies have been developed with the final aim of assessing and comparing the performance of different types of PV modules and technologies in specific geographical locations and under various climatic conditions. These studies can be limited to the performance estimation of one PV technology [2] in certain local conditions rather than the performance comparison of different PV technologies in one location [3–5] or different locations [6,7]. However, the comparisons are limited to the technical aspects and do not take economics into account, or take them into account only marginally. Instead, the relationship between PV module performance and profitability is fundamental to evaluate which PV technology is preferable in a specific location.

The relationship between PV module performance and profitability is influenced both by initial investment and by maintenance operations. Typical PV plant maintenance operations include PV module cleaning and routine scheduled preventive maintenance of PV components, like visual inspections of modules, inverters, wirings, and solar tracking systems (if present). Moreover, extraordinary maintenance operations can be necessary if failures are detected by the plant monitoring system. In particular, the accumulation of dirt (soiling) could have a significant impact on PV module performance. The literature reports general recommendations regarding cleaning method and frequency [8], as well as

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Nomenclature

A	surface area of PV modules [m^2]
a-Si	amorphous silicon cells
$C_0^{O\&M}$	operation and maintenance costs [€/kWp]
C_0^{Tax}	tax cost [€/kWp]
CdTe	cadmium telluride cells
DIN	Department of Industrial Engineering
e	inflation rate [%]
E	DC electrical energy produced in a defined time interval [Wh]
E_y	yearly AC electrical energy production [kWh/year]
F_t	net cash flow at year t [€/kWp]
F_0	initial investment [€/kWp]
G	measured global irradiance [W/m^2]
GaAs	triple-junction III–V gallium arsenide cells
G_{STC}	irradiance at STC [W/m^2]
HE	HEnergia
HIT	heterojunction with intrinsic thin layer cells
i	discount rate [%]
I	irradiation energy in a defined time interval [Wh]
LCOE	levelized cost of energy [€/kWh]
n	period of investment evaluation [number of years]
NPV	net present value [€/kWp]
O&M	operation and maintenance
PEM	proton exchange membrane
P_{DC}	measured DC power [W]
P_{nom}	nominal DC power (or peak power) [W]
Poli c-Si	polycrystalline silicon cells
PR	performance ratio [%]
PRe	corrected performance ratio [%]
PV	photovoltaic
R_0^{Energy}	profits due to PV energy self-consumption [€/kWp]
R_0^{Tax}	cost reduction due to tax deduction [€/kWp]
R_{fv}	loss factor [%]
$r_{O\&M}$	operation and maintenance escalation rate [%/year]
t	time [year]
T_m	PV module temperature [°C]
STC	Standard Test Condition
Y_A	array yield [Wh/W]
Y_R	reference yield [Wh/W]
μc-Si	microcrystalline silicon cells
η_{STC}	DC efficiency at STC [%]
η_{DC}	DC efficiency of PV modules [%]
γ	temperature coefficient [%/°C]

information about performances decreasing due to soiling: two PV plants installed in Southern Italy were monitored, showing a power loss in the range 1–7% depending on the soil characteristic and cleaning method [9], while similar experiences carried on in Egypt showed that even if PV modules are cleaned every day by non-pressurized water, a 50% power decreasing can be measured after 45 days [10]. The soiling phenomenon has also been studied at laboratory scale [11]: power decreasing in the range 2–7% has been found to be dependent on cleaning frequency, rainfall and PV module inclination. The assessment of the profitability of investment in the realization of a PV plant should thus consider not only investment costs and revenues, but also maintenance and operation costs. The maintenance and operating costs are usually ignored or roughly estimated when the feed-in tariff is present, since it usually ensures satisfactory pay-back times and investment productivity. When incentives are marginal, or almost non-existent, operating and maintenance costs become a significant item in the economic evaluation of the investment, and specific models should be developed to evaluate maintenance activity impact on both performance and costs. An economic evaluation of PV system losses due to soiling was made for a PV plant installed in Milan (Italy) and five months was defined as the optimum maintenance interval [12].

Hera S.p.A. is one of the largest Italian multiutility companies (over 8500 employees and more than 3.5 million citizens served) and operates mainly in environmental services (waste collection and treatment), energy services (distribution and sale of electricity and gas) and water services (waterworks, sewerage and purification). At the end of September 2013, Hera inaugurated the applied research center on renewable energy called “HEnergia” (Fig. 1), a test site designed and created in collaboration with the Department of Industrial Engineering (DIN) of the University of Bologna, where different kinds of renewable energy plants are hosted [13]. HEnergia (HE) is located in the industrial area of Forlì, Italy (44°13′21″N-12°02′27″E). More in detail, the research center includes:

- eight different PV plants,
- one combined thermal and PV module plant,
- one parabolic dish solar thermal concentrator (integrated with an absorber chiller), and
- one hydrogen plant, consisting of one electrolyzer, one hydrogen compressor, two storage tanks and three Proton Exchange Membrane (PEM) fuel cells.

HE focuses its activity on testing and analysis of technologies already available on the market, thus achieving multiple know-how objectives, the main ones being:

(i) evaluating yields in a direct and comparative manner of each single component under different operating and environmental conditions,
(ii) verifying how these yields evolve over time, and
(iii) identifying management and maintenance actions and costs.

The paper analyses experimental measurements produced by the PV plants hosted in HE in the period from 1st June 2013 to 28th October 2014 and relates the performances to environmental conditions and maintenance and operation activities. Moreover, the paper evaluates the PV technology investments through the application of the Levelized Cost of Energy (LCOE) and the Net Present Value (NPV) methods.

2. Material and methods

2.1. The PV plants and monitoring system

In the spring of 2013, eight different PV plants were installed in HE. The PV plant differentiation by cell technology, by tracking system and by concentrating optic device is summarized in Table 1, where each plant is identified by a letter. In particular, the following PV cell technologies are present: Heterojunction with Intrinsic Thin layer (HIT), polycrystalline (poli c-Si), cadmium telluride (CdTe), amorphous silicon with microcrystalline silicon (a-Si/μc-Si), and triple-junction III–V gallium arsenide cells (GaAs). Fixed and mono-axial tracked plants are installed with an inclination angle of 30°. All PV plants are South-exposed.

For each technology a string feeds energy via standard inverter into the grid and it is monitored and logged on the DC and AC side of the inverter, with the exception of CdTe device, which has two