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Photovoltaic energy yield modelling under desert and moderate climates: What-if exploration of different cell technologies

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ABSTRACT

PV module testing under standard conditions is an important and well-established procedure, which plays a vital role in module rating. However, PV modules rarely operate at standard conditions therefore their field performance should be predicted based on long term outdoor monitoring or by means of models – so called energy yield models, which combine PV module characteristics with varying environmental conditions. The present work employs a bottom-up, physics-based energy yield modelling approach, which accounts to the interacting optical, thermal and electrical mechanisms in a detailed manner. Additionally, measured data is used for the accurate calibration of the models. Such an approach permits to explore the influence of cell- and module technology details on energy yield under any specific environmental conditions. The present work employs such a method to evaluate the influence of Silicon solar cell technology on energy yield under desert and moderate climates, where the interplay of different irradiance and ambient temperature levels result in a challenging PV performance prediction problem. The purpose of this work is to identify the best-suited solar cell technologies and to understand the underlying mechanisms, which lead to superior PV performance under specific climate conditions. The study is performed by means of physics-based exploratory energy yield simulations with detailed resolution of the thermal effects. Our comparison of four different cell technologies in monofacial modules highlights that superior illumination-dependent performance can contribute to annual energy yield enhancement under both moderate and desert climates amounting to 1.75% and 0.4%, respectively; while a 0.04%/°C advantage in relative temperature coefficient increases annual energy yield (by 1.2%) only under a desert climate.

1. Introduction

Countries of the Middle-East and North Africa (MENA) region are characterized by very high energy consumption per capita (World Bank, n.d.). Due to the climate, the main contributors for such high consumption are air conditioning and water desalination plants. An intensive further rise of electricity consumption is predicted in Kuwait, reaching 65% by 2035, mainly caused by economic development (Alsayegh, 2015). In view of the Paris climate agreement countries of the region set ambitious goals for replacing fossil fuel sources with renewable ones. As an example for the region, the strategic target of Kuwait is to achieve a renewable energy share of 15% by 2030 (Alsayegh, 2015).

The MENA region is known to be abundant in sunshine and therefore solar energy is expected to be one of the dominant contributors to the future energy mix. According to a study carried out by the Kuwait Institute for Scientific Research (KISR), during summer months 60–70% of the generated electric energy is consumed by air conditioning (A/C) systems (Alsayegh, 2015), whose peak consumption corresponds to highest solar irradiation on both daily and seasonal basis. This suggests that generating electricity using PV technology would naturally help to match the load and generation profiles. On the other hand, the vast availability of solar resources comes with significant challenges for PV plants linked to hot and arid climates. Hence to enable cost-effective PV plant design, next to solar irradiance one should also consider the impact of elevated ambient temperature, which causes elevated solar cell operating temperature. This in turn deteriorates photovoltaic cell performance and module reliability.

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Nomenclature

Al-BSF	Full Aluminum Back Surface Field
A/C	air conditioning
α	coefficient of Varshni relation [eV/K]
β	coefficient of Varshni relation [K]
β_t^{model}	modelled V_{oc} temperature coefficient [mV/deg]
c-Si	Crystalline Silicon
DC	direct current
DHI	Diffuse Horizontal Irradiance [W/m^2]
DNI	Direct Normal Irradiance [W/m^2]
ΔI_{sc}	error of short circuit current [%]
ΔV_{oc}	error of open circuit voltage [%]
ΔP_{MPP}	error of maximum power [%]
EOT	Electrical-Optical-Thermal
EVA	ethylene-vinyl acetate
E_g	bandgap energy [eV]
$E_{g,ref}$	bandgap energy at reference temperature [eV]
GHI	Global Horizontal Irradiance [W/m^2]
η_{rel}	relative efficiency [–]
I	current [A]
$I(t)$	irradiance at time t [W/m^2]
I_L	light-generated current [A]
I_{sc}	short-circuit current [A]
I_0	reverse saturation current [A]
$I_{0,ref}$	reverse saturation current at reference temperature [A]
IAM	Incidence Angle Modifier
I-V	current-voltage characteristics
J_L	light-generated current density [mA/cm^2]
J_0	reverse saturation current density [fA/cm^2]
k	Boltzmann's constant (1.38066E − 23 J/K)
KISR	Kuwait Institute for Scientific Research
MENA	Middle-East and North Africa
MPPT	Maximum Power Point Tracking
MPP	Maximum Power Point
n	diode ideality factor
N	north
N_s	number of series-connected cells
n-PERT	n-type Passivated Emitter Rear Totally Diffused
P_{corr}	power without low-illumination efficiency reduction [W]
P_{MPP}	Power at Maximum Power Point [W]
PV	photovoltaic
q	electron charge (1.60218E − 19 Coulomb)
P	power [W]
PR	performance ratio [–]
p-PERC	p-type Passivated Emitter Rear Cell
RC	resistive-capacitive
R_s	series resistance [Ω]
R_{sh}	shunt resistance [Ω]
R_p	parallel resistance [Ω]
SHJ	Silicon Heterojunction
STC	Standard Test Condition
t	time [s]
T	temperature [K]
TC	temperature coefficient (of V_{oc}) [mV/deg]
TC_{rel}	relative temperature coefficient [%/deg]
T_{ref}	reference temperature [K]
V	voltage [V]
V_{oc}	open circuit voltage [V] or [mV]

The significance of thermal effects is determined by the interplay between the thermal response of the solar cells, module materials, installation conditions, local wind conditions and other conditions causing thermal non-uniformities within modules. Consequently, designing and optimizing photovoltaic systems for desert climates should simultaneously account for all of these parameters. Such an optimization issue can be tackled only by physics-based exploratory modelling of PV energy conversion, taking into account measured environmental conditions; cell electrical and thermal behavior, operating point; optical absorption and generation; thermal conduction, convection and radiation. This approach enables the founded extrapolation of module performance to different PV cell, module and system technologies without the necessity of calibration with outdoor data, which is – in turn – often required by parametric models.

While including all of the stated effects, the present work focuses on quantifying the performance impact of the interaction between climatic conditions and solar cell thermo-electrical behavior in order to identify cell technologies, which have the potential to maximize PV energy yield under desert climates. The performance impact is evaluated in terms of energy yield: the output energy divided by the peak power produced at Standard Test Conditions (kW_p). The unit of energy yield is therefore kWh/kW_p.

The employed modelling approach ensures the transparency of the findings by giving access to detailed parameters such as time series of cell temperature, current and voltage. In order to enable a more general understanding of how Energy Yield depends on cell technologies and climate conditions, simulation results for a moderate, North-West European climate are also presented and used for comparison.

The following section (Section 2) introduces the main features and the particular settings of the modelling approach, followed by describing the studied cell and module technologies and the input climate datasets. The results of the simulations are presented and discussed in Section 3. Finally, Section 4 summarizes the main conclusions of the work.

2. Energy yield modelling

The energy yield modelling approach used in the present work employs a bottom-up, physics-based approach. The coupled Electrical, Optical and Thermal (EOT) modelling framework requires first, measured meteorological data: ambient temperature, irradiance, wind speed and direction; second, material properties: optical, thermal and electrical constants, thicknesses of each layer in the module; third, cell and module technology parameters such as electrical behavior of the cell, temperature coefficients, External Quantum Efficiency, module/cell interconnect layout serve also as input. A full description and demonstration of this modelling approach can be found in Goverde et al. (2014, 2015, 2013) and Anagnostos et al. (2014).

The employed approach has been developed not only for accurately modelling the energy yield of PV cells, modules and larger systems on a physics basis but also for enabling the exploration to new technologies. Since the focus of this work is such an exploration study, a detailed description of the model set-up is provided in the next sections.

2.1. General features of the PV energy yield modelling framework

It is well known that the photovoltaic energy conversion process is a result of multiple, strongly coupled physical phenomena, which require an interdisciplinary modelling approach. Light interacts with the module materials through reflection, transmission and absorption. The absorbed light is then converted into electric current and voltage within the semiconductor material. The conversion generates – next to charge carriers – also heat, which deteriorates the conversion efficiency giving importance to thermal effects in PV devices. The removal of the generated heat depends on the employed materials and the convective, conductive and radiative heat transfer processes. Due to the varying