Solar Energy 155 (2017) 445–463

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

A 6-focus high-concentration photovoltaic-thermal dish system

Max Schmitz [a], Nicolay Wiik [a], Gianluca Ambrosetti [b], Andrea Pedretti [b], Stephan Paredes [c], Patrick Ruch [c], Bruno Michel [c], Aldo Steinfeld [a,*]

[a] ETH Zurich, Dept. of Mechanical and Process Engineering, 8092 Zurich, Switzerland
[b] DSolar Ltd, Via Industria 10, 6710 Biasca, Switzerland
[c] IBM Research – Zurich, 8803 Rüschlikon, Switzerland

ARTICLE INFO

Article history:
Received 10 April 2017
Accepted 29 May 2017

Keywords:
Solar dish
CPV
Photovoltaic-thermal
Optical design
Characterization
Performance modeling

ABSTRACT

We present the design, optical characterization and full-system modeling of a novel 6-focus, high-concentration photovoltaic-thermal solar polygeneration system, aiming at an energy-efficient and cost-effective utilization of the solar resource. Essential to this system is a compact, modular solar dish concentrator design optimized for mass-production, structural rigidity, and scalability, with a high geometric concentration ratio of 1733× at each of its six receivers. Every receiver comprises 36 triple-junction CPV cells, interconnected in a unique hybrid parallel-serial scheme that mitigates mismatch losses caused by non-uniform irradiance distributions. Cogeneration is enabled by using high-performance microchannel heat exchangers, allowing the extraction of low grade heat for secondary thermal processes. The tested prototype achieves an average solar radiative flux of 1374 suns on each of the receivers. By optimizing several design parameters, the CPV-thermal system can deliver a solar-to-electricity conversion efficiency of 28.5% in PV-only mode and 26.6% in cogeneration mode while extracting heat at 89.8 °C, and a power of 12.1 kW_{el} and 11.3 kW_{el}/21.5 kW_{th} respectively, matching the performance of state of the art CPV commercial systems, while striving towards a reduction of the investment costs.

1. Introduction

The fundamental principle behind concentrating photovoltaics (CPV) is the substitution of expensive cell area with inexpensive optics (Luque and Andreev, 2007; Pérez-Higueras and Fernández, 2015). As a consequence, high-efficiency multi-junction cells, with a recently demonstrated record photovoltaic efficiency of 46.0% (Green et al., 2016), can be employed. However, in order for an economic benefit to be upheld, several requirements need to be met. The cost per active area of the optical concentrator has to be substantially lower than the cost per area of the cells to offset the additional system costs (Cooper et al., 2016; Ittner, 1980), mandating the use of inexpensive materials, efficient fabrication and assembly, high concentrations, and suggesting the use of large concentrator apertures to reduce the specific number of system components. While a high concentration – beyond several 100 suns – is a key driving factor for cost decrease due to the reduced cell area, it introduces the problem of thermal management of the cells (Algora, 2004; Ittner, 1980). To maintain safe operating conditions at high photovoltaic efficiencies, active cell cooling is required to evacuate the produced heat, which, even with the highest-efficiency cells, is typically more than 50% of the total incident solar radiation, from the dense-arrays. Conversely, if heat can be efficiently extracted at high enough temperatures using photovoltaic-thermal (PVT) receivers (Paredes et al., 2015; Zimmermann et al., 2015), this heat can then be used further in applications such as space heating, cooling, and water desalination, and increase the overall solar resource utilization (Mittelman et al., 2009; Mittelman et al., 2007; Ong et al., 2012).

In this work, we address the aforementioned challenges in an effort to develop an energy-efficient and cost-effective viable solution for solar energy utilization relying on polygeneration of electricity and heat. We present the design concept of a novel modular, multi-focus solar dish for CPV applications. Characterization and modeling of its optical components is coupled to a CPV receiver model for forecasting the on-sun performance under various operating conditions and for design optimization.

2. A modular 6-focus solar dish concentrator

2.1. Multi-module asymmetric solar dish

Line focus (2D) designs can in theory reach a geometrical concentration of $C_{g,ideal,2D} = 1/\sin\theta_i = 215\times$ for a half-acceptance angle $\theta_i = 4.65$ mrad (Winston et al., 2005). However, practical designs

* Corresponding author.
E-mail address: aldo.steinfeld@ethz.ch (A. Steinfeld).

http://dx.doi.org/10.1016/j.solener.2017.05.087
0038-092X/

Nomenclature

Latin characters

$A_{act,rec}$	$36 \cdot A_{cell}$, Active receiver area, m^2
A_{cell}	active cell area, m^2
A_{rec}	receiver area, m^2
c	irradiance coefficient of the short-circuit current, A/W
c_p	mass-specific heat capacity of the cooling water, kJ/(kg·K)
$C_{g,ideal,2D}$	thermodynamic limit of concentration in line-symmetry (2D)
$C_{g,ideal,3D}$	thermodynamic limit of concentration in line-symmetry (3D)
d_m	projected active area diameter of a mirror facet, m
D	density of the cooling water, kg/m^3
DNI	direct normal irradiance, W/m^2
E	irradiance, W/m^2
$E_{av,cell}$	cell-averaged irradiance, W/m^2
$\langle E_{av,cell} \rangle$	mean cell-averaged irradiance, W/m^2
$E_{av,cell,max}$	maximum cell-averaged irradiance, W/m^2
$E_{av,LFPC\text{-}rec}$	average irradiance over the LFPC-receiver, W/m^2
$E_{av,rec}$	average irradiance over the PV receiver, W/m^2
E_{max}	peak irradiance, W/m^2
f	focal length, m
f_{obj}	objective function, –
F	irradiance scaling factor, $W/(m^2 \cdot GV)$
F_{corr}	corrected irradiance scaling factor in the region outside of the ROI, $W/(m^2 \cdot GV)$
FF	fill factor, %
F	focal point, –
GV	gray value, GV
I	current, A
J	current density, A/cm^2
J_0	diode saturation current density, A/cm^2
J_{ph}	photocurrent density, A/cm^2
k	module index, –
k_B	Boltzmann constant, $1.380649 \cdot 10^{-23}$ J/K
l_{cond}	effective length of the conductor, m
n_D	diode ideality factor, –
N_m	number of concentrator modules, –
P	electrical power, W
q	elementary charge, $1.602176 \cdot 10^{-19}$ C
$\dot{Q}_{cells}$	radiative power incident on the active area of the PV receiver, W
$\dot{Q}_{LFPC\text{-}rec}$	total power incident on the LFPC-receiver, W
$\dot{Q}_{rec}$	total power incident on the PV receiver, W
$\dot{Q}_{refl.,1}$	total power reflected by the primary mirrors, W
$\dot{Q}_{ROI}$	solar radiative power absorbed in the ROI, W
$\dot{Q}_{solar}$	solar radiative power incident on the mirror aperture, W
$\dot{Q}_{thermal}$	total thermal power absorbed in the cells, W
r	radial coordinate, m
R	electrical resistance, Ω
R_b	electrical resistance of a bottom electrode segment, Ω
$R_{b,cnt}$	electrical contact resistance between the cell and submodule bottom electrodes, Ω
$R_{b,pl}$	electrical resistance of the bottom electrode plate, Ω
R_{bar}	electrical resistance of the submodule interconnection bars, Ω
R_f	radial translation of the focal point, m
R_i	inner mirror perimeter, m
R_o	outer mirror perimeter, m
R_s	lumped model series resistance, Ω
R_{sh}	lumped model shunt resistance, Ω
$R_{t,300}'$	electrical resistance of a free grid finger segment of thickness 300 μm, Ω
$R_{t,300}$	electrical resistance of a cell-connected grid finger segment of thickness 300 μm, Ω
$R_{t,400}'$	electrical resistance of a free grid finger segment of thickness 400 μm, Ω
$R_{t,400}$	electrical resistance of a cell-connected grid finger segment of thickness 400 μm, Ω
$R_{t,600}'$	electrical resistance of a free grid finger segment of thickness 600 μm, Ω
$R_{t,600}$	electrical resistance of a cell-connected grid finger segment of thickness 600 μm, Ω
$R_{t,cnt}$	electrical contact resistance between the cell and submodule top electrodes, Ω
$R_{t,pl}$	electrical resistance of the top electrode plate, Ω
R_{term}	electrical resistance of the receiver terminals, Ω
R_{th}	thermal resistance of the high-performance cooler chip, cm^2 K/W
t_{cond}	thickness of the conductor, m
t_{rel}	relative temperature coefficient of the photovoltaic efficiency, 1/K
T	temperature, °C
$T_{av,cell}$	average cell temperature, °C
$T_{av,rec}$	average receiver temperature, °C
T_{in}	coolant inlet temperature, °C
T_{out}	coolant outlet temperature, °C
T_{ref}	reference temperature, °C
V	voltage, V
$\dot{V}_{rec}$	receiver coolant flow rate, l/min
w_{cond}	width of the conductor, m
x	spatial coordinate, m
y	spatial coordinate, m
z	spatial coordinate, m

Greek characters

α	angle in circumferential direction, defining the position of a focal point, °
α_{cell}	fraction of radiation incident on the active area that is not converted into electrical power, %
α_{te}	absorptance of the copper top electrode, %
$\beta_{1\text{-}5}$	independent fitting parameters for the PV cell efficiency at MPP
$\gamma_{LFPC\text{-}rec}$	intercept factor on the LFPC-receiver, %
$\Delta\Phi$	$= \Phi_2 - \Phi_1$, rim span, °
ε_{Voc}	error at open circuit of a *J-V* curve fit, –
ε_{η}	error at MPP of a *J-V* curve fit, –
ζ	factor accounting for the loss in active area fraction due to gaps between the glued mirror segments and for soiling of the mirrors, %
$\eta_{el,rec}$	$= \eta_{opt,rec} \cdot \eta_{MPP,rec}$, electrical receiver efficiency, %
$\eta_{MPP,rec}$	electrical efficiency at MPP of a PV receiver module, %
η_{opt}	$= \zeta \cdot \rho_{mirror} \cdot \eta_{window} \cdot \eta_{SOE}$, optical solar-to-receiver (concentrator) efficiency, %
$\eta_{opt,rec}$	optical receiver efficiency, %
η_{SOE}	SOE efficiency, %
$\eta_{sol.\text{-}to\text{-}el.}$	$= \eta_{opt} \cdot \eta_{el,rec}$, full-system solar-to-electricity efficiency, %
η_{window}	window transmission efficiency, %
θ_i	acceptance half-angle, °
$\rho_{Al2O3,Al}$	8°/hemispherical reflectance of the Al_2O_3 coating on an aluminum substrate, %
$\rho_{Al2O3,Cu}$	8°/hemispherical reflectance of the Al_2O_3 coating on a copper substrate, %
ρ_{mirror}	solar-averaged mirror reflectance, %
σ	electrical conductivity, $\Omega^{-1} \cdot m^{-1}$
$\sigma_{err,1}$	angular dispersion error standard deviation in circumferential direction, mrad