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A high-efficiency hybrid high-concentration photovoltaic system

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ABSTRACT

Photovoltaic power generation is a growing renewable primary energy source, expected to assume a major role as we strive toward fossil fuel free energy production. However, the photovoltaic efficiencies limit the conversion of solar radiation into useful power output. Hybrid systems extend the functionality of concentrating photovoltaics (CPV) from simply generating electricity, to providing simultaneously electricity and heat. The utilization of otherwise wasted heat significantly enhances the overall system efficiency and boosts the economic value of the generated power output. The current system consists of a scalable hybrid photovoltaic–thermal receiver package, cooled with an integrated high performance microchannel heat sink. The package can be operated at elevated temperatures due to its overall low thermal resistance between solar cell and coolant. The effect of the harvested elevated coolant temperature on the photovoltaic efficiency is investigated. The higher-level available heat can be suitable for sophisticated thermal applications such as space heating, desalination or cooling (polygeneration approaches). A total hybrid conversion efficiency of solar radiation into useful power of 60% has been realized. The exergy content of the overall output power was increased by 50% through the exergy content of the extracted heat. An analysis based on the economic value of heat illustrates that the reused heat can double the economic value of such a system.

1. Introduction

The energy demand of the world is continuously rising due to ever increasing global population and industrialization [1]. At present, energy from non-renewable resources such as fossil fuels or fissionable materials accounts for over 92% of the world energy usage [2]. In addition, energy generation based on burning of fossil fuels has caused an increase in carbon dioxide (CO_2) and other greenhouse gas emissions, leading to global warming. A switch from fossil fuels to renewable energy sources such as sun, wind or water has become one of the major challenges of the 21st century. Harvesting solar energy is a promising technology for renewable power generation with the potential to meet a significant proportion of the world's energy needs. There are many alternatives available to directly harness the sun's energy, the most prevalent of which are solar collectors designed to generate thermal energy and photovoltaic cells generating electricity, the latter being the main focus in this paper.

However, generating electric power from solar radiation through photovoltaic conversion is dominated by technologies using one material for the solar cell. This approach limits the conversation efficiency to about 25%. Although highest efficiencies can be reached using multi-junction solar cells [3] their fabrication costs still pose a limiting factor. Therefore, in concentrating photovoltaic (CPV) systems the sunlight is collected by concentrating optics and focused onto a considerably smaller photovoltaic receiver. Thus, this technology substitutes expensive photovoltaic cell material by inexpensive optical equipment. This approach reduces the cost per produced kilowatt-hour [4,5]. Some of the first concentrator systems used Fresnel lenses [6] or compound parabolic concentrators [7] to achieve concentration of the sunlight. Higher concentrations of up to 1000 suns were mainly achieved through the use of solar tower reflectors in the center of multiple heliostats [8] and parabolic dish based systems [5,9–11]. The latter are suitable for various applications ranging from small rooftop photovoltaic power stations to high concentration photovoltaic thermal systems with concentration of 2000 suns [12].

Despite very different designs, all solar concentrator systems share some key requirements. Thermal management and temperature control are among the most important aspects in any

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Nomenclature

A	receiver area (m^2)
C	concentration ratio
c_p	specific heat capacity (J/kg K)
DNI	direct normal irradiance (W/m^2)
EEVC	enhanced economic value coefficient
$\dot{E}x$	exergy (W)
h	enthalpy (J/kg)
I	current (A)
$\dot{m}$	mass flow rate (kg/s)
P	power (W)
PR	price ratio
$\dot{Q}$	heat (W)
R_{th}	thermal resistance (K/W)
s	entropy (J/kg K)
T	temperature (K)
U	utility function
V	voltage (V)

Greek letters

Δ	difference between inlet and outlet
η	efficiency
λ	thermal conductivity
χ	price for 1 kW h of energy

Subscripts

0	reference from ambient
comb	combined (electrical and thermal)
el	electric
ff	fossil fuels
he	heat to electricity
in	inlet
max	maximum
MP	at the maximum point
oc	open circuit
out	outlet
pump	pump
sc	short circuit
Sol	solar
sun	sun
th	thermal

concentrator system because of the generated high power densities. Especially CPV systems require strict temperature control because of the strong influence of the operation temperature on the photovoltaic conversion process. The electrical efficiency and, consequently, the power output of a photovoltaic module depend linearly on the operating temperature [13]. High concentration ratios impact the system performance in several ways. First, photovoltaic efficiency increases with increasing irradiance (up to a design specific limit) [14]. Second, high concentration involves high heat fluxes and, consequently, the design of the heat exchanger and the selection of an appropriate coolant become of paramount importance [15]. However, increasing concentration reduces the influence of temperature on photovoltaic efficiency [16–20]. If high concentrating photovoltaic (HCPV) systems were to serve as viable source to appreciably meet the global energy demand, a systemic approach addressing the high efficiency requirements and potential of both the photovoltaic and cooling components is needed. Despite high photovoltaic conversion efficiencies, more than 50% of the potential power output is dissipated as heat. Therefore, advancements with respect to overall solar energy collection and usage of the heat in photovoltaic systems will boost the overall energy efficiency significantly. Photovoltaic thermal collectors have been investigated intensively for lower concentrations and it has been shown that this approach significantly enhances the efficiency [21,22].

The current work introduces and investigates a hybrid High Concentration Photovoltaic–Thermal (HCPVT) system designed to achieve optimal overall module efficiency. This includes the maximal generation of electricity and the associated harvesting of produced thermal power enabling its further utility. A related system has been modeled previously to look at multi junction solar cells in a solar concentration energy system with active cooling [23]. The thermal requirements of these hybrid solar receivers are very similar to micro processors in high performance computing. To this end, the recently demonstrated technologies for energy management in high performance computing [24,25] can be integrated synergistically in HCPVT systems. Approaches for reuse of otherwise wasted heat demonstrated in supercomputers [26] and datacenters [27,28] can be used to boost the energy efficiency on in HCPVT systems. The operating temperature of the PV cells is controlled to allow direct reuse of the collected heat at the required temperature level, and is simultaneously kept low-enough to maintain high electrical efficiency. A direct reuse of heat from HCPVT systems targets the replacement of heat generated by combustion of fossil fuels (also a wasteful approach in terms of exergy), thereby reducing the global carbon footprint.

The temperature of the wasted heat is pivotal to assess its value for potential reuse. In terms of exergetic content, thermal energy is inferior to electric energy, because it cannot be efficiently converted to mechanical energy (Carnot-limited conversion). Additionally, thermal energy carriers are usually difficult to transport. An exergy [29] analysis of any system can provide crucial information about the usefulness of the collected energy [30–32].

The present work focuses on the thermal characteristics of the photovoltaic package and includes a complete energy and exergy analysis of an experimental prototype rooftop photovoltaic power station based on a parabolic dish concentrator. In a final step, different reuse strategies such as space heating, desalination and refrigeration based on adsorption cooling for the collected heat of HCPVT systems are evaluated to substantiate the enhancement in economic value. The research lays the foundation for developing a new generation of hybrid photovoltaic–thermal systems with integrated energy reuse and minimal carbon footprint.

2. Experimental setup

The investigated setup and its different components are shown in Fig. 1. A description of the different components and their characteristics is presented in the sequel.

2.1. Photovoltaic converter

A single-junction GaAs monolithic interconnected module (MIM) solar cell was chosen for a proof of principle demonstration. The dimensions of the cell were 21 mm × 21 mm with a thickness of 0.5 mm. MIMs consist of several photovoltaic cell segments, which are series-connected during cell fabrication process [33,34]. In this approach the photovoltaic area is divided in several series-connected segments leading to a high voltage and low current device. Because of the low current, power losses due to series resistances can be kept small. The applied MIM consisted of 23