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Roadmap for the next-generation of hybrid photovoltaic-thermal solar energy collectors

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ABSTRACT

For hybrid photovoltaic-thermal collectors to become competitive with other types of solar energy converters, they must offer high performance at fluid outlet temperatures above 60 °C, as is required for space heating and domestic hot water provision, which together account for nearly 50% of heat demand. A roadmap is presented of the technological advances required to achieve this goal. Strategies for reducing convective, radiative and electrical losses at elevated temperature are discussed, and an experimental characterisation of a novel transparent low-emissivity coating for photovoltaic solar cells is presented. An experimentally-validated simulation formalism is used to project the performance of different combinations of loss-reduction strategies implemented together. Finally, a techno-economic analysis is performed to predict the price points at which the hybrid technologies along the roadmap become competitive with non-hybrid photovoltaic and solar thermal technologies. The most advanced hybrid technology along the roadmap employs an evacuated cavity, a transparent low-emissivity coating, and silicon heterojunction photovoltaic cells.

1. Introduction

The growth of photovoltaic (PV) solar energy capacity worldwide has been hailed as a great leap forward in the battle to curb climate change, reduce dependence on finite fossil fuel reserves, and achieve energy independence for many nations. In the past decade, installed capacity has risen from 5.1 to 320 GWe (Philipps and Warmuth, 2017). Early growth has been stimulated by government subsidies; however, the more recent and substantial upturn has been driven by the ever-falling production costs of crystalline silicon (c-Si) PV modules. As a result, PV solar energy has now reached so-called grid parity in many parts of the world (Rocky-Mountain-Institute et al., 2014; Shah and Booream-Phelps, 2015; Shah et al., 2014), is soon expected to become one of the cheapest forms of energy supply (Green, 2016), and has been projected to represent 35% of global newly installed capacity by 2040 (Bloomberg-New-Energy-Finance, 2015).

As production costs fall and solar penetration becomes significant, we enter into a new era in which module costs are no longer the limiting factor to growth. The new challenges faced are numerous. Firstly, solar generation is intermittent and the daily and annual generation profile does not match demand, meaning that mass energy storage must be employed to enable increased penetration. Secondly, the cost of installation of a PV module is now greater than the production cost (Mayer et al., 2015), and the highest material cost is the encapsulation rather than the PV solar cells (Green, 2016). Thirdly, if solar generation is to be deployed in a distributed nature – close to the point of use – then the amount of suitable space for installations will become increasingly scarce, particularly in urban environments. In light of these considerations, it is believed that PV technologies will increasingly have to compete on overall power density (i.e. watts per unit area), and not only on the cost-per-watt of the module, which is presently the most commonly cited figure of merit (Green, 2016).

Conversely, solar thermal (ST) collectors have relatively high collection efficiencies up to 80%, (Solar-Rating-and-Certification-Corporation, 2007) low costs at around 1–8 €-ct/kWh (Mauthner et al., 2014), and are mature, with 435 GW_{th} installed globally (REN21, 2016). Nonetheless, ‘the annual rate of installed capacity is far less than for PV, largely since thermal energy is presently considered less

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Nomenclature

Abbreviations

PV	photovoltaic(s)
c-Si	crystalline silicon
PVT	photovoltaic-thermal
ST	solar thermal
CSP	concentrating solar power
IEA	International Energy Agency
ITO	indium tin oxide
NOCT	nominal operating cell temperature
DHW	domestic hot water
EVA	ethylene vinyl acetate
NIST	National Institute of Standards and Technology (U.S.)
MIR	mid-infrared
DMD	dielectric-metal-dielectric
TCO	transparent conductive oxide
CIGS	copper indium gallium selenide
Al-BSF	aluminium back surface field
PERC	passivated emitter rear contact
HJT	heterojunction technology
ARC	anti-reflection coating
PR	performance ratio
AR	annual revenue
FiT	feed in tariff
SPF	seasonal performance factor
PBP	payback period

Symbols: Relating to PV cells

η	efficiency (%)
T_{cell}	cell temperature (°C)
η_{STC}	efficiency under standard test conditions (%)
β	temperature coefficient

Relating to PVT collectors

η_{th}	thermal efficiency (%)
η_{opt}	optical efficiency (%)
a	linear heat loss coefficient ($W\,m^{-2}\,°C^{-1}$)
T_m	mean fluid temperature (°C)
T_a	ambient temperature (°C)
ε	emissivity (dimensionless)
α	absorptivity (dimensionless)

Relating to the techno-economic analysis (Subscripts denote electrical (el) or thermal (th) outputs. Superscripts denote PV, PVT or ST collectors. e.g. YelPVT is the annual electrical energy yield of a PVT collector)

Y	annual energy yield ($kWh\,m^{-2}\,year^{-1}$)
η	collector efficiency (%)
PR	performance ratio (%)
H	annual insolation ($kWh\,m^{-2}\,year^{-1}$)
T_d	fluid delivery temperature (°C)
p	price at which energy is sold or price of energy displaced ($)
AR	annual revenue generated from energy output ($\$\,m^{-2}\,year^{-1}$)
CS	carbon savings from total energy output ($kgCO_2\,m^{-2}\,year^{-1}$)
CI	carbon intensity of displaced energy ($kgCO_2/kWh$)
SPF	seasonal performance factor of heat pump (dimensionless)
PBP	payback period (years)
C	total system cost including collector, rest of system and installation ($)

valuable than electricity, is more difficult to transport without losses and new infrastructure, and is less versatile. However, a great advantage of thermal energy that will become of increasing importance is that it can be stored more efficiently and cheaply than electricity (Branz et al., 2015). Moreover, nearly half of the energy consumed globally is finally used as heat (International-Energy-Agency, 2012), generated either using gas, electricity, oil, biomass or other sources. Using distributed ST collectors equipped with thermal storage to displace electricity demand for heat generation is therefore a viable means of increasing solar penetration whilst dealing with intermittency of the solar resource. Solar heat therefore holds a great deal of untapped potential.

Within a high-penetration landscape, many benefits are offered by hybrid photovoltaic-thermal (PVT) collectors, which generate both electricity and thermal energy from a single aperture area (Zondag, 2008). These have a similar electrical efficiency to purely PV modules (Good et al., 2015), but with an added thermal efficiency of up to 60% (under low temperature operation) (Zondag, 2008). It has already been pointed out that employing concentrating PVT in centralized power plants can help address the storage challenge, whilst maximising the economic value of the energy produced per unit installation area, as compared to purely PV or concentrating solar power (CSP) power plants (Branz et al., 2015). However, considering that nearly half of the energy consumed globally is finally used as heat (International-Energy-Agency, 2012), it is clear there is also a significant opportunity to deploy distributed PVT collectors on residential, industrial and commercial sites, and to store and use the generated thermal energy to directly satisfy the local heat demand, whilst using the electricity either on-site or distributing via the grid.

In spite of the above considerations, the uptake of PVT has so-far been extremely modest. The installed capacity is presently too low to be reported, although a number of commercial products have appeared on the market (Good et al., 2015; International-Energy-Agency, 2008). Cited barriers to growth include product immaturity, a lack of specific standards (Good et al., 2015) (although these have been recently introduced (Network, 2015)), and reliability concerns over collector longevity due to daily thermal cycles, which is a topic of ongoing research (Magalhães et al., 2016).

A more fundamental barrier is the often-cited dilemma faced by PVT technology: both the electrical and thermal efficiency decrease with the PV-cell temperature, whereas the utility of the delivered thermal energy increases with this temperature. The majority of PVT systems deployed to date have aimed at delivering low temperature heat (< 40 °C). Unglazed panels, which have particularly high heat losses, are often favoured for these low-temperature applications, since they keep the PV cells cooler, and so improve electrical efficiency. However, a low-temperature thermal output is able to satisfy relatively few end-use demands, e.g. swimming pool heating, which represent a tiny proportion of global heat demand; thus reducing the market potential of PVT as compared to purely PV or solar-thermal collectors.

PVT technology would achieve a significantly greater market potential if it were optimised to deliver thermal energy at temperatures of 40–60 °C. These temperatures are sufficient for domestic hot water (DHW) and space heating. As an example, roughly 50% of U.S heat demand requires temperatures in this range (Fox et al., 2011), corresponding to around 20% of total U.S final energy use (Philibert, 2006). A more ambitious strategy would therefore be to optimise PVT collectors to deliver thermal energy at these higher temperatures, whilst mitigating thermal and electrical losses, and ensuring collector longevity. There are now glazed collectors on the market that go some way towards achieving this (ENERGIES-SOL, 2015; Solimpeks, 2016)).