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Hybrid photovoltaic-thermal solar systems for combined heating, cooling and power provision in the urban environment

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ABSTRACT

Solar energy can play a leading role in reducing the current reliance on fossil fuels and in increasing renewable energy integration in the built environment, and its affordable deployment is widely recognised as an important global engineering grand challenge. Of particular interest are solar energy systems based on hybrid photovoltaic-thermal (PV-T) collectors, which can reach overall efficiencies of 70% or higher, with electrical efficiencies up to 15–20% and thermal efficiencies in excess of 50%, depending on the conditions. In most applications, the electrical output of a hybrid PV-T system is the priority, hence the contacting fluid is used to cool the PV cells and to maximise their electrical performance, which imposes a limit on the fluid's downstream use. When optimising the overall output of PV-T systems for combined heating and/or cooling provision, this solution can cover more than 60% of the heating and about 50% of the cooling demands of households in the urban environment. To achieve this, PV-T systems can be coupled to heat pumps, or absorption refrigeration systems as viable alternatives to vapour-compression systems. This work considers the techno-economic challenges of such systems, when aiming at a low cost per kW h of combined energy generation (co- or tri-generation) in the housing sector. First, the technical viability and affordability of the proposed systems are studied in ten European locations, with local weather profiles, using annually and monthly averaged solar-irradiance and energy-demand data relating to homes with a total floor area of 100 m^2 (4–5 persons) and a rooftop area of 50 m^2. Based on annual simulations, Seville, Rome, Madrid and Bucharest emerge as the most promising locations from those examined, and the most efficient system configuration involves coupling PV-T panels to water-to-water heat pumps that use the PV-T thermal output to maximise the system's COP. Hourly resolved transient models are then defined in TRNSYS, including thermal energy storage, in order to provide detailed estimates of system performance, since it is found that the temporal resolution (e.g. hourly, daily, yearly) of the simulations strongly affects their predicted performance. The TRNSYS results indicate that PV-T systems have the potential to cover 60% of the combined (space and hot water) heating and almost 100% of the cooling demands of homes (annually integrated) at all four aforementioned locations. Finally, when accounting for all useful energy outputs from the PV-T systems, the overall levelised cost of energy of these systems is found to be in the range of 0.06–0.12 €/kW h, which is 30–40% lower than that of equivalent PV-only systems.

1. Introduction

The energy problem is multifaceted and complex, and involves a number of important aspects such as the continued increase in the global energy demand in the face of stagnating oil production, price volatility, concerns relating to energy independence, security and economic growth, and a growing awareness of the detrimental effects on health and the environment of releasing combustion products into the atmosphere [1,2]. Renewable energy sources provide a secure and reliable solution for the decarbonisation of the energy infrastructure, and are associated with significantly reduced cradle-to-grave emissions. However, renewable energy sources currently supply only 14% of the world's total energy [3], with solid biofuels having the largest share, mainly in the non-commercial sector in developing countries.

Solar energy is a clean, abundant and sustainable form of primary energy [4] that can address the energy problem simultaneously from economic, environmental, health and security perspectives [5,6], and the realisation of affordable solar energy systems has been widely acknowledged as a global engineering grand challenge. Within a European framework, where this study

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Nomenclature

AC air conditioning
AR absorption refrigeration
COP coefficient of performance
DHW domestic hot water
HP heat pump
LCOE levelised cost of energy
MPP maximum power point
PV photovoltaic
PV-T photovoltaic-thermal

List of symbols

A total solar collector array aperture or gross area [m^2]
c_P specific heat capacity of the collector fluid [J/kg K]
F_R overall solar collector heat removal factor when the efficiency is given in terms of T_{in} [–]
F_m modified value of F_R when the solar collector efficiency is given in terms of T_m [–]
I global radiation incident on the solar collector (tilted surface) [W/m^2]
M_i mass of the fluid in the i^{th} storage tank segment [kg]
m mass flow rate at use conditions [kg/s]
m_{test} mass flow rate at test conditions [kg/s]
m_L fluid mass flow rate from the storage tank to the load [kg/s]
m_h fluid mass flow rate to the storage tank from the heat source [kg/s]
P_{elec} PV electrical power output [W]
Q_i rate of thermal energy input by the heating element to the i^{th} storage tank segment [W]
T_a ambient temperature [°C]
S_h number of the storage tank segment into which the fluid enters from the heat source, $S_h = 1, \ldots, 4$ [–]
S_L number of the storage tank segment into which the fluid enters when replacing that extracted to supply the load, $S_L = 1, \ldots, 4$ [–]
T_h temperature of the fluid entering the storage tank from the heat source [°C]
T_L temperature of the fluid replacing that extracted to supply the load [°C]
T_m average temperature of the fluid through the solar collector [°C]
T_{in} inlet temperature of the fluid to the solar collector [°C]
T_i temperature of the i^{th} storage tank segment [°C]
T_o outlet temperature of the fluid from the solar collector [°C]
T_{PV} PV temperature [°C]
T_{PVo} PV reference temperature [°C]
t time [s]
U_L overall thermal loss coefficient of the solar collector per unit area [W/m^2 K]
U'_L thermal loss coefficient dependency on temperature [W/m^2 K^2]
α short-wave absorptance of the absorber plate [–]
α_i control function defined by $\alpha_i = 1$ if $i = S_h$, and $\alpha_i = 0$ otherwise [–]
β PV temperature coefficient [1/°C]
β_i control function defined by $\beta_i = 1$ if $i = S_L$, and $\beta_i = 0$ otherwise [–]
γ_i control function defined by $\gamma_i = f(\alpha_i, \beta_i)$ [–]
τ short-wave transmittance of the collector cover(s) [–]
$(\tau\alpha)$ product of the cover transmittance and the absorber absorptance [–]
$(\tau\alpha)_n$ product $(\tau\alpha)$ at normal incidence [–]
η_{PV} PV efficiency [–]
η_{TH} thermal efficiency [–]
ΔU_i incremental loss coefficient between the i^{th} storage tank segment and the environment per unit area [W/m^2 K]

is focussed, it has the potential to play a leading role in meeting the requirements of European Directives (2010/31/EU, 2012/27/EU) which aim to reduce fossil-fuel consumption and to increase the integration of renewables in the built environment. It can be utilised in a wide range of diverse applications, from providing space heating, hot water and cooking, to generating power for lighting, cooling, and generally for supporting the electrical infrastructure. These attributes have been promoting an increasing interest in academia, industry and governments worldwide in research, innovation and investments related to solar energy technologies [7,8].

Despite its advantages, solar energy remains a small fraction of the world's total energy supply (below 2%) [9]. Most of the global solar-driven generation is in China and OECD countries, with an annual global growth of 46% for PV and 11% for solar thermal, and especially strong growth in Europe [10], as a result of the implementation of policies and subsidies supporting the adoption of relevant technologies. If solar energy is to play a significant role within the energy-mix, this will involve an ever-increasing quantity of distributed energy generation in the urban and built environment. This transition has the benefit of moving generation closer to the point of use, into areas where the population is dense and real estate is expensive, thus reducing the load on the energy distribution infrastructure. In order to maintain a low cost of solar energy generation, it is necessary not only for the solar energy generators to be low cost, but also for the high-quality energy being generated per m^2 of roof coverage to be maximised. This need can be met by hybrid photovoltaic-thermal (PV-T) systems, which generate both electricity and useful thermal energy from the same aperture area, and can easily be integrated with other energy technologies (conversion, storage, etc.) in order to provide multiple energy outputs while making efficient use of an available roof area. Such hybrid PV-T collectors are capable of reaching overall (electrical plus thermal) efficiencies of 70% or higher, with electrical efficiencies up to 15–20% and thermal efficiencies in excess of 50%, depending on the conditions [11]. Solar systems are resilient to oil/gas price fluctuations and political instability since most of their costs are upfront investment costs while running (operating, maintenance) costs are minimal. Solar systems allow for independence or self-consumption, whereby the user generates the energy required onsite with only limited interaction with the local grid, thus significantly reducing their electricity bills. Self-consumption is only possible when renewable systems are interconnected and the electricity and heat generated in excess is stored or used for multiple purposes [12].

Adding to the advantages offered by solar PV and hybrid PV-T systems are reliability and life-time. These systems can be expected to operate with little deterioration for more than 20 years. Reported observations of operational PV systems have shown a loss in power output of 0.5% per year on average [13], while only 2% of modules installed do not meet manufacturer's warranties after 10 years [14]. At present, a small number of manufacturers are producing PV-T systems, despite the relative immaturity of the technology [15]. In most cases, commercial PV-T systems simply integrate existing PV modules and solar thermal