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A UK-based assessment of hybrid PV and solar-thermal systems for domestic heating and power: System performance

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HIGHLIGHTS

- We develop a mathematical model to simulate a hybrid solar-thermal system (PVT).
- Household electricity and hot water demands covered throughout a year are estimated.
- Two key system parameters are varied to optimise the system performance.
- Up to 51% of the annual electrical and 36% of the hot water demands are covered.
- In addition, 16.0 tCO_2 (35% higher than PV-only) are saved over a 20-year lifetime.

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ABSTRACT

The goal of this paper is to assess the suitability of hybrid PVT systems for the provision of electricity and hot water (space heating is not considered) in the UK domestic sector, with particular focus on a typical terraced house in London. A model is developed to estimate the performance of such a system. The model allows various design parameters of the PVT unit to be varied, so that their influence in the overall system performance can be studied. Two key parameters, specifically the covering factor of the solar collector with PV and the collector flow-rate, are considered. The emissions of the PVT system are compared with those incurred by a household that utilises a conventional energy provision arrangement. The results show that for the case of the UK (low solar irradiance and low ambient temperatures) a complete coverage of the solar collector with PV together with a low collector flow-rate are beneficial in allowing the system to achieve a high coverage of the total annual energy (heat and power) demand, while maximising the CO_2 emissions savings. It is found that with a completely covered collector and a flow-rate of 20 L/h, 51% of the total electricity demand and 36% of the total hot water demand over a year can be covered by a hybrid PVT system. The electricity demand coverage value is slightly higher than the PV-only system equivalent (49%). In addition, our emissions assessment indicates that a PVT system can save up to 16.0 tonnes of CO_2 over a lifetime of 20 years, which is significantly (36%) higher than the 11.8 tonnes of CO_2 saved with a PV-only system. All investigated PVT configurations outperformed the PV-only system in terms of emissions. Therefore, it is concluded that hybrid PVT systems offer a notably improved proposition over PV-only systems.

1. Introduction

A significant increase in energy demand has been observed in the last decades, driven by an increase in population and/or in the energy use per capita in various regions around the globe. In the UK, energy use per capita has actually decreased by about 15% since its peak in the late 1990s, which has more than compensated for the ~10% increase in population over the same period [1]. There is a significant and continuing desire to maintain this trend, and to diversify and decarbonise the energy supply, thus lowering the reliance on fossil fuels, which arises from the realisation that these are finite resources (giving rise to economic, security of supply and sustainability concerns) and also that the emissions associated with their use lead to wider environmental and health problems [1]. Specifically, the UK has made a number of international commitments and set itself a series of targets for reducing greenhouse gas emissions and increasing the proportion of final energy supplied by renewable sources [2].

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Nomenclature

Abbreviations

a-Si	amorphous-crystalline PV module
c-Si	mono-crystalline PV module
pc-Si	poly-crystalline PV module
MPP	Maximum Power Point
NOCT	Normal Operating Cell Temperature
PV	photovoltaic
PVT	PV and solar-thermal system
PVT/w	PV and solar-thermal water system

Symbols

A_c	collector aperture area (m^2)
A_{PV}	surface area of the PV (m^2)
c_p	specific heat capacity of water (=4180 J/kg K)
D	diameter of the riser tubes (m)
DC_{av}	percentage of the average overall demand covered by the PVT system (%)
DC_E	percentage of the electricity demand covered by the PVT system (%)
DC_{HW}	percentage of the hot water demand covered by the PVT system (%)
DC_{wav}	percentage of the weighted average overall demand covered by the PVT system (%)
e_{ag}	thickness of the air gap (m)
e_i	thickness of the insulation layer (m)
E_{grid}	electrical energy required from the grid over a full year (kW_e h)
E_{loss}	electrical energy consumed by the water pump (kW_e h)
E_{net}	additional (to the PVT-generated) electrical energy required to cover the short-fall in the household demand over a full year (kW_e h)
E_{neti}	additional (to the PVT-generated) electrical energy required to cover the short-fall in the household demand at time step *i* (W_e h)
E_{PV}	electrical energy produced by the PV-only system over a full year (kW_e h)
E_{PVT}	electrical energy produced by the PVT system over a full year (kW_e h)
E_{PVTi}	Electrical energy produced by the PVT system at time step *i* (W_e h)
E_{PVTnet}	net electrical energy available from the household after subtraction of the household's consumption over a full year (kW_e h)
E_T	total annual electricity demand (kW_e h)
E_{wd}, E_{we}	electricity consumption over a day, either during the week or on the weekend respectively (kW_e h)
Em_{aux}	total CO_2 (equivalent) emissions due to the auxiliary heater over a full year (kg CO_2(e))
Em_{cE}	total CO_2 (equivalent) emissions from covering the total electricity demand from the grid over a full year (kg CO_2(e))
Em_{cHW}	total CO_2 (equivalent) emissions from covering the overall hot water demand with an equivalent conventional system (natural gas boiler, heat pump or electrical heater) over a full year (kg CO_2(e))
Em_{PVTE}	total CO_2 (equivalent) emissions incurred to cover the demand with an installed PVT unit over a full year (kg CO_2(e))
Em_{sE}	percentage of CO_2 (equivalent) emission savings due to the electricity demand covered by the PVT system (%)
Em_{sHW}	percentage of CO_2 (equivalent) emission savings due to hot water production by the PVT system (%)
Em_{sT}	total CO_2 (equivalent) emissions saved over a full year when PVT systems are used to cover the demand (kg CO_2(e)/year)
f	Darcy–Weisbach (or Moody) friction factor for the water flow through the pipes
g	gravitational acceleration (=9.81 m/s^2)
G_{bi}	thermal conductance between the absorber, the back/underside insulation and the environment (W/m^2 K)
G_{ca}	thermal conductance between the PV laminate layer and the absorber plate (W/m^2 K)
Gr	Grashof number
h_{air}	free convective heat transfer coefficient of air at the back/underside of the PVT module (W/m^2 K)
h_w	convective heat transfer coefficient of the water flow in the pipes (W/m^2 K)
h_{wind}	convective heat transfer coefficient due to wind flow over the PVT (W/m^2 K)
J	incident global solar irradiance on the tilted PVT collector surface (W/m^2)
k_{air}	thermal conductivity of air (W/m K)
k_i	thermal conductivity of the insulation layer (W/m K)
k_w	thermal conductivity of water (W/m K)
K_s	minor loss coefficient for flow through a bend
L	total length of the water pipe (m)
$\dot{m}_c$	mass flow-rate of water through the collector (kg/s)
$\dot{m}_l$	mass flow-rate of hot water demand (kg/s)
$\dot{m}_t$	mass flow-rate of water through the heat-exchanger located in the hot water tank (kg/s)
$\dot{m}_{tube}$	mass flow-rate of water flowing through the riser tubes of the collector (kg/s)
M_t	total mass of water in the hot water tank (kg)
NTU	Number of Transfer Units
Nu	Nusselt number
P	PV area covering factor (%)
P_{net}	net electrical power output of the PVT system (W)
P_{PV}	electrical power output of the PV module (W)
P_P	electrical power consumed by the water pump (W)
P_{wd}, P_{we}	electrical power demand at a specific time of the day, either during the week or on the weekend (W)
$\dot{q}_{ag}$	heat flux from the glass cover to the PV laminate layer due to both conduction and convection through the air gap (W/m^2)
$\dot{q}_{agab}$	heat flux from the glass cover to the absorber plate due to convection through the air gap in the uncovered section without PV (W/m^2)
$\dot{q}_{aux}$	auxiliary heater power (W)
$\dot{q}_{bi}$	heat flux through the back/underside insulation (W/m^2)
$\dot{q}_{biab}$	heat flux through the back/underside insulation in the uncovered section without PV (W/m^2)
$\dot{q}_{ca}$	heat flux from the PV laminate to the absorber (W/m^2)
$\dot{q}_{caab}$	heat flux through the absorber plate in the uncovered section without PV (W/m^2)
$\dot{q}_{ct}$	heat addition from the collector to the hot water tank (W)
$\dot{q}_{loss}$	heat losses through the hot water tank walls (W)
$\dot{q}_{load}$	heat removal to cover the domestic hot water demand (W)
$\dot{q}_{rPV}$	heat flux from the glass cover to the PV laminate due to radiation (W/m^2)
$\dot{q}_{rab}$	heat flux from the glass cover to the absorber plate due to radiation (W/m^2)
$\dot{q}_{sky}$	heat flux loss between the glass cover and the sky due to radiation (W/m^2)
$\dot{q}_{skya}$	heat flux loss from the glass cover to the sky in the uncovered section without PV due to radiation (W/m^2)
$\dot{q}_w$	heat flux transferred from the absorber to the water (W/m^2)