Applied Energy 161 (2016) 512–532

Contents lists available at ScienceDirect

Applied Energy

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

Hybrid PV and solar-thermal systems for domestic heat and power provision in the UK: Techno-economic considerations

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HIGHLIGHTS

- Renewable heat and power generation in UK homes with PVT systems studied.
- PVT/w generation: 2.3 MW_e h/yr (51% of demand) and 1.0 MW_{th} h/yr (36% hot water).
- Optimised PVT/w system has 9–11 year payback periods (PV-only: 6.8 years).
- Same system allows 16.0-t CO_2 reduction and 14-t primary fossil-fuel saving.
- With a ~2:1 support (£/W_e h:£/W_{th} h), PVT and PV have similar payback periods.

ARTICLE INFO

Article history:
Received 16 April 2015
Received in revised form 30 June 2015
Accepted 4 September 2015
Available online 26 October 2015

Keywords:
Hybrid PVT
Domestic UK energy
Combined heat and power
Solar energy

ABSTRACT

A techno-economic analysis is undertaken to assess hybrid PV/solar-thermal (PVT) systems for distributed electricity and hot-water provision in a typical house in London, UK. In earlier work (Herrando et al., 2014), a system model based on a PVT collector with water as the cooling medium (PVT/w) was used to estimate average year-long system performance. The results showed that for low solar irradiance levels and low ambient temperatures, such as those associated with the UK climate, a higher coverage of total household energy demands and higher CO_2 emission savings can be achieved by the complete coverage of the solar collector with PV and a relatively low collector cooling flow-rate. Such a PVT/w system demonstrated an annual electricity generation of 2.3 MW h, or a 51% coverage of the household's electrical demand (compared to an equivalent PV-only value of 49%), plus a significant annual water heating potential of to 1.0 MW h, or a 36% coverage of the hot-water demand. In addition, this system allowed for a reduction in CO_2 emissions amounting to 16.0 tonnes over a life-time of 20 years due to the reduction in electrical power drawn from the grid and gas taken from the mains for water heating, and a 14-tonne corresponding displacement of primary fossil-fuel consumption. Both the emissions and fossil-fuel consumption reductions are significantly larger (by 36% and 18%, respectively) than those achieved by an equivalent PV-only system with the same peak rating/installed capacity. The present paper proceeds further, by considering the economic aspects of PVT technology, based on which invaluable policy-related conclusions can be drawn concerning the incentives that would need to be in place to accelerate the widespread uptake of such systems. It is found that, with an electricity-only Feed-In Tariff (FIT) support rate at 43.3 p/kW h over 20 years, the system cost estimates of optimised PVT/w systems have an 11.2-year discounted payback period (PV-only: 6.8 years). The role and impact of heat-based incentives is also studied. The implementation of a domestic Renewable Heat Incentive (RHI) at a rate of 8.5 p/kW h in quarterly payments leads to a payback reduction of about 1 year. If this incentive is given as a one-off voucher at the beginning of the system's lifetime, the payback is reduced by about 2 years. With a RHI rate of 20 p/kW h (about half of the FIT rate) PVT technology would have approximately the same payback as PV. It is concluded that, if primary energy (currently dominated by fossil fuels) and CO_2 emission minimisation are important goals of national energy policy, PVT systems offer a significantly improved proposition over equivalent PV-only systems, but at an elevated cost. This is in need of careful reflection when developing relevant policy and considering technology incentivation. Currently, although heat outweighs electricity consumption by a factor of about 4 (by energy unit) in the UK domestic sector, the support landscape has strongly favoured electrical microgeneration, being inclined in favour of PV technology, which has been experiencing a well-documented exponential growth over recent decades.

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http://dx.doi.org/10.1016/j.apenergy.2015.09.025
0306-2619/© 2015 The Authors. Published by Elsevier Ltd.

Nomenclature

Abbreviations

BOS	Balance of System costs
COP	Coefficient of Performance
CPBT	Cost Payback Time
CPI	Consumer Price Index
DPB	Discounted Payback Period
FIT	Feed-In Tariff
MPP	Maximum Power Output
NPV	Net Present Value
NOCT	Normal Operation Cell Temperature
LPC	Levelised Production Cost
LCC	Levelised Coverage Cost
LCS	Life Cycle Savings
PV	photovoltaic
PVT	photovoltaic and solar-thermal system
PVT/w	photovoltaic and solar-thermal water system
RHI	Renewable Heat Incentive
RHPP	Renewable Heat Premium Payment
a-RHPP	Augmented Renewable Heat Premium Payment
a-RHPP*	Optimum Augmented Renewable Heat Premium Payment
RPI	Retail Price Index
STC	Standard Test Conditions

Symbols

β_0	temperature coefficient for the PV module (1/K)
A_i	annual costs incurred by the system (£/year)
A_{inet}	annual costs incurred by the system (£/year) once the RHI is discounted ($A_{inet} = A_i$ – RHI)
C_0	total upfront cost of a project (£)
C_{aux}	total running costs of the auxiliary heater throughout the year (£/year)
C_{cE}	total running costs of buying the overall electricity demand from the grid throughout the year (£/year)
C_{cHW}	total running costs of a conventional system throughout the year (£/year)
C_e	electricity price (p/kW$_e$ h)
C_{NG}	natural gas price (p/kW$_{th}$ h)
$C_{O\&M}$	operation and maintenance costs of the unit throughout the year (£/year)
C_{PVE}	total running costs incurred to cover the demand when a PV-only unit is installed (£/year)
C_{PVTE}	total running costs incurred to cover the demand when a PVT unit is installed (£/year)
C_{sE}	percentage of cost savings due to the electricity demand covered by the PVT system (%)
C_{sHW}	percentage of cost savings due to hot-water production (%)
d	discount rate for the PVT system (%)
d_c	discount rate for the conventional system (%)
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 (%)
DPB	Discounted Payback Period (years)
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_{PVT}	electrical energy produced by the PVT system over a full year (kW$_e$ h)
E_{PVTnet}	net electrical energy generated and 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)
i	inflation rate (%)
J	incident global solar irradiance on the tilted PVT collector surface (W/m^2)
k	time steps
L	levelised cost (£/year)
LCC$_{av}$	Levelised Coverage Cost per percentage of average demand covered (L (£/year)/DC$_{av}$ (%/year))
LCC$_E$	Levelised Coverage Cost per percentage of electrical demand covered (L (£/year)/DC$_E$ (%/year))
LCC$_{HW}$	Levelised Coverage Cost per percentage of hot-water demand covered (L (£/year)/DC$_{HW}$ (%/year))
LCC$_{wav}$	Levelised Coverage Cost per percentage of weighted average demand covered (L (£/year)/DC$_{wav}$ (%/year))
LPC	Levelised Production Cost (p/kW h)
n, N	lifetime of the PVT system
NPV	Net Present Value (thousand £, or £'000)
P	PV area covering factor (%)
P_{PV}	electrical power output of the PV module (W)
PW$_{LCS}$	present worth of LCS (£)
PW$_n$	present worth of an investment cost at the end of year n (£)
Q_{aux}	total auxiliary energy required over a full year (kW$_{th}$ h)
Q_{gas}	additional amount of heat required (kW$_{th}$ h)
Q_{PVT}	amount of hot-water produced by the PVT system over a full year (kW$_{th}$ h)
Q_T	total household hot-water demand over a full year (kW$_{th}$ h)
RHI	Renewable Heat Incentive (p/kW$_{th}$ h)
T_{cin}	temperature of the water entering the collector (K)
T_{cout}	temperature of the water exiting the collector (K)
T_{del}	delivery temperature of hot water to the household (K)
T_l	delivery temperature of hot water from the auxiliary heater (K)
T_{PVout}	temperature of the water entering the uncovered section without PV (K)
T_{sup}	mains water supply temperature (K)
T_t	temperature of the water in the hot-water tank (K)
T_{tin}	temperature of the collector flow at the inlet of the heat exchanger immersed in the hot-water tank (K)
T_{tout}	temperature of the collector flow at the outlet of the heat exchanger immersed in the hot-water tank (K)
T_{win}	temperature of the water entering the hot-water tank (K)
$(UA)_t$	overall heat transfer coefficient-area product of the heat exchanger located inside the water storage tank (W/K)
V_P	water flow-rate through the collector (with 1 L/h = 2.78×10^{-7} m^3/s)

1. Introduction

For various and in different cases distinctive reasons, energy generation, management (including transportation, storage, supply) and consumption in all their facets have recently received increasing attention in both developed and developing countries. In the former case, assisted by public opinion, this has been driven by a desire for energy diversification and decarbonisation in an effort to move away from the existing reliance on fossil fuels and towards a more secure, clean and sustainable energy portfolio. In the latter, including in China, India and the rest of the BRICKs, this has also arisen in response to the strong economic (and corresponding energy demand) growth that is being experienced and a desire to raise living standards that are correlated with higher energy use [1,2]. In both cases, these trends have helped establish renewable energy technologies as an indispensable means of energy production, with major (often exponential) growth experienced in the sector in recent decades.

In the EU it is believed that by means of several pathways, such as improved energy efficiency measures and the development of renewable technologies, it is possible to meet the imposed energy targets of: (i) a 20% reduction of greenhouse gas emissions; and (ii) an increase in the proportion of final energy consumption from renewables to 20% by 2020 [3]. In the particular case of the United Kingdom, where the present research effort is based, the Renewable Energy Directive has set a national target of 15% for the fraction of total energy coming from renewable sources by 2020 in order to meet this EU-wide goal [4]. In addition to this commitment, the recasting of the Energy Performance of Buildings Directive of the EU has set a target according to which all new buildings have to be nearly zero-energy buildings and most of the required energy should come from renewable sources by 31st December 2020 [5].

In particular, solar-based renewable systems can be deployed to deliver not only electricity, but also hot water, space heating and even cooling, depending on the specific requirements and the technologies used. In residential buildings, which are at the focal point of the present study, solar-thermal collectors and photovoltaic (PV) systems are highly suitable options for onsite renewable energy generation. The former can provide a thermal energy output for direct water or space heating, while the latter can provide electrical energy to cover partially a household's electricity needs. Furthermore, a combined hybrid PV and solar-thermal system (PVT) is an alternative solar energy solution, which offers the distinct advantage of providing from a single unit both a thermal output (e.g. for water heating), as well as an electrical output with an improved efficiency compared to stand-alone PV modules if designed correctly [6–9]. The present paper is based on hybrid PVT systems because the associated research is concerned with the distributed supply of both electricity and hot water in the domestic sector, where this technology is expected to have its greatest potential due to the combination of both PV and solar-thermal collectors in a single system. This synergistic combination allows for the electrical and thermal outputs to be obtained simultaneously while at the same time reducing the losses in the electrical efficiency of the PV module that are caused by the increase in temperature from the solar irradiation. The loss reduction is achieved by using a cooling flow of (heated) water through the solar collector unit.

Clearly, the development of the above mentioned solar-based systems and technologies has a very significant role to play in contributing towards the emission and renewable energy targets of the EU and the UK, while decreasing the primary energy consumption in the building sector [10]. Nevertheless, their uptake is heavily affected by high upfront costs. Further technical advancements as well as additional investment in existing and future solar technologies are necessary in order to make these systems an affordable proposition by reducing their costs, as well as to ensure an appropriate infrastructure within which they can operate [11,12]. Questions related to the costs and benefits of hybrid PVT systems serve as the primary motivation for the present work.

Both the electricity and the hot-water usage in households are strongly dependent on household/user behaviour. Therefore, in order to size, design and estimate the outputs and costs of hybrid PVT systems properly for domestic heating and power, it is important to understand and to characterise their local demand profiles [13]. The present paper investigates the suitability of a hybrid PVT system installed on the roof of an average three-bedroom terraced house located in London, the UK, by means of a techno-economic assessment. This analysis is based on the detailed whole-system hybrid model (PVT unit, hot-water storage tank, auxiliary heater and household) developed in previous work [14], with varying temporal local profiles of solar irradiance and household demands over the course of an entire year, allowing predictions of the full annual performance of the system.

The goal of the work reported in Herrando et al. [14], by exploring the role of important system parameters and evaluating the performance of a range of PVT/water (PVT/w) system configurations and operating strategies, was to maximise the combined production of electricity and hot water in an average house in London, the UK. In addition, the PVT outputs were compared to a PV-only equivalent system and also to a reference case based on the same house using conventional technologies (a mix of natural gas boilers, heat pumps and electrical heaters with a share according to UK technology-uptake statistics) [14].

The present paper complements this previous study by considering the economics of the deployment of PVT technology, based on the most suitable configurations identified in that study. Particular emphasis was placed on simplicity of design, leading to a minimisation of system costs to the end-user. Therefore, a commercial sheet-and-tube PVT/w unit was taken as a basis design for the solar collector. Certain key system parameters were required to develop the model and to study its performance, which were not provided by the manufacturer. These were estimated in our previous study [14], and are also used herein.

A number of investigators have undertaken excellent earlier research in this field, in which different approaches were used to estimate the performance and economics of PVT systems [8,15–18]. The present paper attempts to extend our knowledge in a number of directions. Firstly, almost all earlier studies were based in countries at relatively low latitudes with a significant solar resource, whereas the present study explores a possible deployment of PVT technology in the UK, which is representative of cooler northern climates with lower levels of solar irradiation. This is expected to significantly affect the results, not only due to the different environmental conditions, but also due to the very different set of Government policies, incentives, electricity and gas prices, household energy demands, etc. Secondly, earlier studies considered constant economic parameters such as the inflation and discount rates, or constant 'daily average' profiles for the demands; in the present research a parametric analysis is undertaken to study explicitly the influence of those economic parameters, and the demands are allowed to vary throughout the whole year. Furthermore, a third novelty of the present paper is that it explores variations to financial incentives, both for (electricity) microgeneration and renewable hot-water production, and in particular, attempts to compare the payback of PVT and PV technology, leading to an identification of the incentive levels that would place the two on similar paybacks. Typically, previous studies either did not consider Government support, considered a single incentive level, or only electricity-related subsidies. Beyond comparisons with a PV-only system, we also compare PVT technology with conventional alternative. The PV-only system considered has the same installed capacity as the investigated PVT units, while the conventional reference case is based on the same house using a mix of technologies for hot-water production (mainly natural-gas boilers, but also including electrical heaters and heat pumps) and electricity bought from the grid, as defined in Ref. [14]. Fourthly, this paper concerns the application of PVT systems at scales relevant to the distributed electricity and hot-water generation in the domestic sector, as opposed to larger/industrial scales of application with very different economics (e.g. [15]).

It should also be noted that there have been a number of interesting techno-economic analyses focused on hybrid systems featuring PV, however, those studies considered PV in conjunction with wind, battery, or diesel generators [19–22] rather than hybrid PVT systems. There are also other studies, such as the one by Beccali et al. [23] that considers PVT/air systems coupled with desiccant cooling (with a fixed level of Government incentives, without variations), however, it is believed that PVT/w systems are more suitable for the specific case-study represented by the present paper. To the best of our knowledge, based on the previous paragraphs, this is the first such UK-based effort of its kind.

In what follows, firstly, the hybrid PVT concept is described in Section 2. This is followed in Section 3 by a presentation of the techno-economic methodology used in this work, including a complete statement of the various system parameters and how these were obtained or estimated. This leads in Section 4 to a presentation and discussion relating to our main results. Finally, conclusions are drawn in Section 5.

2. Hybrid PVT systems

2.1. Hybrid system concept overview and motivation

An important limitation of PV modules arises from the decrease in their efficiency experienced when the cells are heated by solar radiation and their temperature increases, leading to a reduced conversion of solar energy into electricity. One way to overcome this problem is to cool the solar cells with an appropriate contacting fluid, flowing either above or below them. The cooling flow not only decreases the temperature of the PV cells, but also produces a stream of hot fluid that can be used for another purpose, such as space or water heating, hence obtaining a useful thermal (in the form of raised enthalpy) output. This has been a key motivating factor behind the development of 'hybrid' solar systems [6,7,9,24,25]. Therefore, a PV/thermal hybrid (PVT) collector system combines in a single unit a PV module, coupled with a heat exchanger containing a suitable heat transfer fluid [7,8,26–28].

In many current applications of hybrid PVT systems, the electrical output is usually the main priority, so the operating conditions of the heat transfer unit are controlled with the maximisation of this output in mind. However, in order to achieve this, the cooling fluid (typically air or water) should be kept at a low temperature to avoid an undesirable decrease in the PV cell electrical efficiency, thus decreasing the usefulness of the thermal output. If, on the contrary, the system is designed to obtain a higher outlet fluid temperature, then the PV cell efficiency will suffer to some extent relative to the optimal electrical power output setting [7,9,28,29], although this is still expected to be higher than the uncooled simple PV equivalent system. Hence, a trade-off is needed depending on the end-user needs. As a consequence of the prioritisation of electricity, these systems are currently less often used than separate PV and thermal collector units, even though according to Tripanagnostopoulos [9], PVT systems have lower cost per unit of electricity and heat produced for the same total surface area needed for their installation.

Several types of hybrid systems exist, but the present paper focuses on PVT water systems (PVT/w), which consist of a PV module in thermal contact with a flow of water within an arrangement similar to a solar-thermal collector. PVT/w systems are considered a particularly efficient mode of preheating water all year long [6,7,9]. Several types of PVT/w systems exist, with different configurations. Of these, the sheet-and-tube PVT collector appears as one of the most promising design options for small-scale, distributed domestic hot-water production because, although it perform slightly (specifically, about 2%) worse than channel PVT collectors, it is a good alternative in terms of thermal efficiency and also an easy configuration to manufacture since it only needs to integrate a standard PV panel onto a standard thermal collector with few modifications, thus relying heavily on well-known and available technology [30].

In a previous study by our group [14] we investigated the operational and performance characteristics of a complete PVT/w system for electricity and hot-water provision to a typical household in London, the UK. An active water-circulation system was selected in this case because, due to the high latitude of the UK, the outdoor temperature can drop below freezing thus requiring an antifreeze liquid in a separate collector fluid-circuit [8,31]. In particular, the effort reported in Herrando et al. [14] was concerned with the optimal flow-rate required from the circulator for the cooling fluid circulation circuit and the fraction of the surface area of the collector exposed to the solar radiation that is covered by PV cells. It was concluded that for the particular UK-based scenario of combined domestic electricity and hot-water supply studied, a high or complete coverage of the solar collector with PV is recommended. This allows the system to achieve a high electrical output, given the low solar radiation available, while the temperature attained by the water flowing through the collector is not too high. This is in agreement with the conclusions of similar efforts [32]. In addition, it was found that with a completely covered collector and a relatively low cooling flow-rate of 20 L/h, 2.3 MW_e h per year or 51% of the total household electricity demand could be covered by the investigated hybrid PVT/w system, along with an added potential for hot-water heating amounting to 1.0 MW_{th} h per year or 36% of the total hot-water demand. This allows for a reduction in CO_2 emissions of 16.0 tonnes over a life-time of 20 years (or, 20 tonnes over 25 years) due to the reduction in the electrical power drawn from the grid and in the fuel used for water heating, which also corresponds to a 14 tonnes displacement of associated primary fossil-fuel consumption (based on natural-gas). Both the emission and fossil-fuel reductions allowed by the PVT installation are significantly larger (by 36% and 18%, respectively) than figures obtained for an equivalent PV-only system. The calculation of the fossil-fuel consumption savings is based on the Lower Calorific Value of natural gas (a value of 54 MJ/kg), an 88% efficient gas-fired boiler [33], a global average efficiency of electricity production of 36% [34], and an 8% electricity transmission and distribution loss [2].

2.2. State-of-the-art commercial hybrid systems

Although hybrid systems are not yet a mature technology and their commercialisation is still at an early stage, there are a number of companies that manufacture PVT air and PVT water systems, as well as concentrating PVT systems. In this section a range of commercial hybrid systems are mentioned, along with their estimated thermal and electrical outputs, and their market price as of 2012 when this data was collected. Manufacturers of such systems are given in the map in Fig. 1, which provides basic performance (electrical and thermal) and cost information. By means of cost comparison, a 4.5 kW ground-source heat pump (suggested for an average

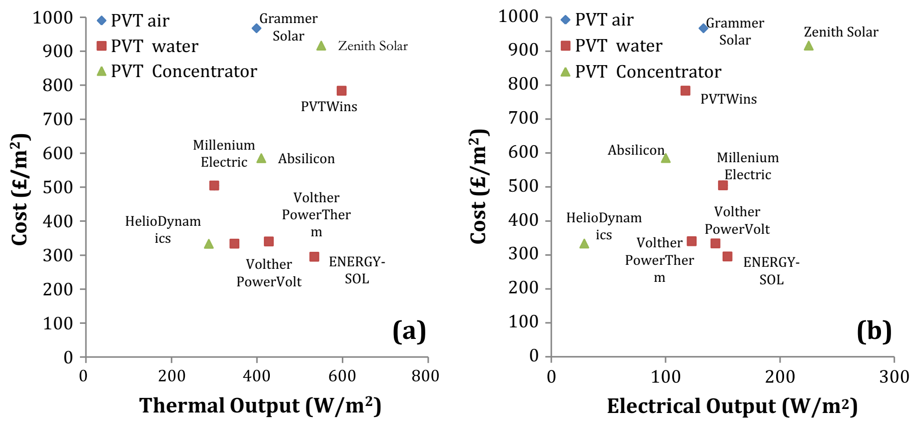

Fig. 1. Summary of commercially available hybrid PVT technologies, in terms of: (a) thermal and (b) electrical output. Both plots show cost (£/m^2) vs. output (W/m^2) as of 2012 when this data was collected. Different PVT technologies are indicated as follows: PVT air (diamonds), PVT water (squares) and PVT concentrator (triangles).

UK home) is around £2700, although this technology still relies on grid-provided (and hence carbon intensive) electrical power in order to supply heat to the household [2].

There are fewer manufacturers of PVT air systems compared to PVT water systems, but their level of commercialisation is somewhat more advanced. Some PVT air systems are specifically intended for office or industrial buildings [35] so they are out of the scope of the present paper, which focuses on the domestic sector. Others [36,37] can be installed in domestic settings to provide space heating (shown in diamonds in Fig. 1). Concentrating PVT systems have also been developed in an attempt to substitute expensive PV cells for relatively cheap concentrating devices which focus the sunlight onto (smaller) PV solar cells [26]. There are some companies manufacturing these systems [38–40] (triangular points in Fig. 1), however, these are based on concentrating parabolic systems with solar tracking, so they are less suitable for affordable, roof-top domestic installation, which is of interest to our study. An interesting concentrating PVT system based on a flat plate format for roof installation was being developed by Chromasum [41], but was not yet commercially available at the time of the present research.

The square points in Fig. 1 correspond to PVT water (PVT/w) units. The figure suggests that among the commercially available PVT systems, PVT/w systems offer an excellent option in terms of price *vs.* thermal and electrical output. The systems manufactured by NewForm Energy (Volther PowerTherm and Volther PowerVolt) [42] and by ENERGIES-SOL [43] appear to be particularly promising. Hence, from these two products/manufacturers, the latter is selected here for further analysis as it provides a greater electrical and thermal output for a similar cost per unit surface area. Most PVT/w system manufacturers have developed their systems by modifying commercial solar-thermal collectors to include a PV module onto their absorber surface [26]. As such, PVT/w units are often based on a flat-plate solar collector with a mono-crystalline PV module thermally attached to its top surface [37,42–44]. This also allows a quick, first-order estimation of the cost of a PVT unit to be made by adding the cost of the solar-thermal collector to that of the PV module, and then subtracting the cost of saved materials due to integrated production and installation. Beyond the cost of the PVT module (see Fig. 1), it is estimated that the cost of the hybrid solar controller is around £750 [42].

2.3. Combined PVT and side-by-side system comparison

Several studies [7–9,29,45] have compared the efficiencies of hybrid PVT water systems with those of side-by-side standard PV modules and solar collectors. Although there are discrepancies in the results found, some conclusions can be drawn. Firstly, the actual performance of a PVT system is strongly dependent on the geographical location [45]. Secondly, the major potential of this technology is the dual output of both electricity and hot water. It should be taken into account that, although both the electrical and thermal yield of a PVT system may be slightly lower than that of a conventional PV or solar-thermal system [26] covering the same total area, PVT systems generate more energy per surface area than the case when *both* PV panels and solar collectors are placed side-by-side, therefore allowing smaller total area when requiring both outputs [30,46]. Hence, an additional advantage appears when the available external building surface area is limited, since PVT systems constitute an integral unit, which is also more aesthetically pleasing and can provide improved architectural uniformity compared to two systems with different appearance [9,27,30].

Furthermore, in terms of costs, hybrid systems can provide potential savings both in material use and in production and installation costs, which means a reduction in the Balance of System (BOS) costs. It is estimated that a PVT module can reduce the (upfront) investment costs by about 10% compared to the joint use of PV and solar collector modules and also has the potential to reduce the financial and energy payback of PV systems [26,27]. This leads to an estimated of Cost Payback Time (CPBT) of PVT systems at present values of about 10–15 years when operating at low temperature according to Tripanagnostopoulos [9] (these values will increase at higher operating temperatures as both electrical and thermal efficiencies are reduced). With regards to the environmental impact, PVT systems are also expected to have a significantly lower energy and CO_2 payback time (around 20–30% lower) than conventional PV modules [9]. It is concluded that PVT systems display important advantages and deserve further investigation. It is noted, nevertheless, that these numerical figures are for the specific case of Greece. Given that these will be very sensitive to the geographical location where the technology is deployed, the present study considers the performance and costs of a PVT/w system in an average UK home, which is a key novelty of this effort.

2.4. Relevant UK Government financial support

A primary barrier for the accelerated uptake of renewable energy technologies arises from their high upfront capital costs compared to conventional fossil-fuel systems, in which a significant fraction of the levelised (i.e. total) costs is incurred during operation (fuel costs). In particular, PV systems are still not competitive and cost effective compared to centralised, conventional fossil-fuel power generation in grid-connected applications [26]. Although the energy payback periods of hybrid PVT systems are expected to be better than for PV, their capital investment is actually higher due to the additional thermally related design features and components required. Hence, long-term, effective and predictable financial incentives are required to overcome the hurdle of their increased upfront investment cost [26,47].

In the UK, one such (previously available) incentive took the form of an investment subsidy known as the Renewable Heat Premium Payment (RHPP), which consisted of a one-off £300 voucher for the installation of a solar-thermal product in any household in England, Scotland and Wales [48]. A second incentive is the Feed-In Tariff (FIT) for renewable electricity generation, which, if appropriately designed, is capable of driving technological development and market expansion. In order to be successful, FITs should include a yearly reduction in accordance with the technical, industrial and market progress [26]. This reduction has already been included in the FITs for different renewable technologies in the UK [49], starting at 43.3 p/kW h in 2010–11 and falling to 18.8 p/kW h in 2020–21 in the case of solar PV with a total installed capacity of 4 kW or lower (the case study in the present paper). It should be noted that this subsidy is a temporary measure and will no longer be necessary once grid parity is reached or surpassed by a particular technology, since at that point the market becomes self-sustained. Loans to help customers pay the high initial investment cost may be kept for about 30 years [12].

At the time of writing, in the UK there is also financial support for solar-thermal systems installed in the non-domestic sector, through the Renewable Heat Incentive (RHI), which consists of quarterly payments made over a 20-year period [50]. The introduction of a second phase of this RHI support to the domestic sector is expected soon, and along with the introduction of the Green Deal for Homes these schemes form long-term tariff support for the domestic sector. In this work we investigate a ‘nominal’ domestic RHI amounting to 8.5 p/kW h, and also study some variations in the resulting economics of PVT technology to changes to the implementation of this incentive scheme.

In summary, the combined electrical and thermal energy yield of hybrid PVT systems make them eligible for a range of subsidies, including FITs for the electricity generated by the solar cell and RHI for the hot water produced by the solar-thermal collector component. And yet, the upfront capital costs remain high. Therefore, to encourage the uptake of these systems and thus to fully harness their potential contribution to the reduction in primary energy and emissions, it may beneficial to consider possible modifications to these incentives or to implement additional ones. For example, a full solar-thermal subsidy [26] would act to incentivise PVT installers, facilitate the deployment in this technology, and accelerate the commercialisation of PVT systems [12,26]. With this in mind, in the present paper we investigate the role of incentivation schemes in affecting the economic proposition of the investigated hybrid PVT/w systems in our selected application and geographical location.

3. Techno-economic methodology

3.1. PVT system modelling

The present study is based on the model developed in Herrando et al. [14], which has been extended here to include additional information (i.e. parameters) relating to the economics of the investigated PVT/w systems. Therefore, as in the earlier work [14], results are generated by the model on a daily basis, which can then be used to calculate the monthly outputs of the system for the different months of the year with the final goal of obtaining the total annual outputs of the system.

The complete modelled system, shown in Fig. 2, comprises an array of PVT units/collectors, a hot-water tank, an auxiliary electrical heater, an adjustable flow circulator, and the necessary connecting flow conduits, also featuring a bypass valve [6]. In this study, the system was split into two main sections: (i) the PVT array with its active cooling water circuit (including the circulator or water pump); and (ii) the storage tank (which includes the auxiliary heater). The two sections are connected by a heat exchanger located inside the hot-water storage tank where thermal energy is transferred from the water flowing through the solar collectors to the water in the tank, after which the flow returns to the collectors where it is re-heated. It is assumed that the pipes connecting the PVT units to the water storage tank are well insulated such that heat losses can be neglected. Therefore, the temperature of the water at the inlet to the collector array is the same as the temperature of the water exiting the bottom of the heat exchanger inside the storage tank, $T_{cin} = T_{tout}$, and the temperature of the water at the collector array outlet is the same as the temperature of the water entering the heat exchanger inside the tank, $T_{cout} = T_{tin}$ [51]. A bypass is required to ensure that the temperature of the water entering the tank is high enough to heat the contained hot water, or $T_{tin} > T_t$ [52].

In addition, an auxiliary heater is required to provide hot water at $T_l = 60$ °C in the case that the temperature of the water stored in the tank is lower than this, i.e. for $T_t < 60$ °C. When the hot water temperature required by the end-user is below 60 °C, a mixing device cools the water before it is directed to the household for use. In the present investigation, a constant supply temperature of $T_{del} = 60$ °C is imposed in order to study the most demanding scenario, so the mixing device is not considered.

The model requires a solar irradiance profile over the course of a day to be specified as an input, as well as the hot-water and electricity demands over a 24-h period; details of how these were specified are provided in Section 3.2. Based on the solar irradiance and demands, the model is run on a daily basis with the use of finite time-elements with an interval of 30 min, in such a way that the 24-h period is divided in a set of 48 inputs/outputs. The solar input and hot-water demand vary depending on the month, while the electricity demand also depends on whether it is a weekday or weekend day. Hence, to obtain annual results, each analysis of the performance of a particular PVT system/configuration is undertaken 24 times (12 months, twice per month; weekday and weekend), which means that the model is run 24 times after which the values are used to obtain total monthly and annual results, as explained in Section 3.3.

It is emphasised that although it is relatively straightforward and unambiguous to consider that the system's electrical output directly displaces electrical energy (and the emissions and primary energy associated with this) that would otherwise have been taken from the grid, the utility of the thermal output requires more subtle consideration. In this work, the thermal output displaces a combination of natural-gas boilers, electrical heaters and heat pumps (and the emissions and primary energy associated with these) as per the current uptake of these technologies in the UK. Details can be found in Section 3.3.

3.1.1. PVT collector array

As explained in the introductory sections above, a sheet-and-tube PVT/w collector was selected for this study. The two main components of such a unit are the PV module and the solar collector, which can be further divided into: glazing, PV module, thermal absorber, riser tubes containing the working fluid and insulation layer. The specific PVT/w collector design chosen here is based

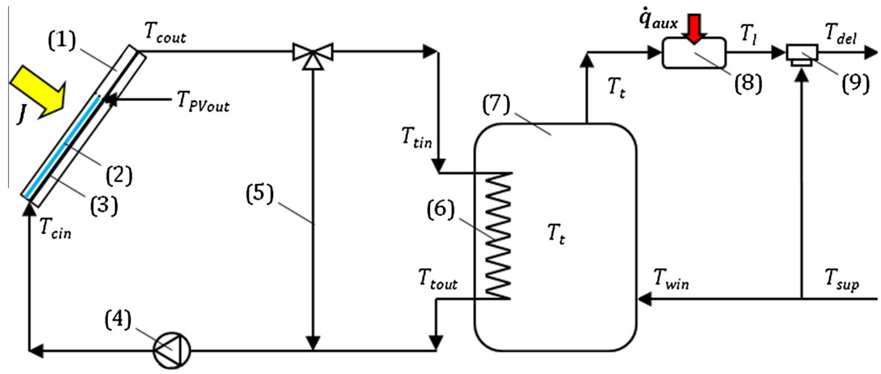

Fig. 2. Schematic diagram of the PVT domestic hot water system: 1. PVT panel, 2. PV module, 3. Solar collector, 4. Water pump, 5. By-pass, 6. Tank heat exchanger, 7. Hot water tank, 8. Auxiliary heater, and 9. Mixing device. Reproduced from Herrando et al. [14].

on the commercially available hybrid system ENERGIES-SOL [43], and the parameters needed to fully define the unit were obtained from the manufacturer's data sheets and the literature [10,30,46,51,53].

The unit of interest comprises a transparent glass cover, an air gap, a mono-crystalline PV module, an EVA encapsulating film, an absorber-exchanger that transforms the solar radiation to heat and transfers it to the collector fluid, and a layer of insulating material at the base [14]. The transparent cover is a single, 3.2-mm thick glass sheet. The absorber–exchanger consists of a sheet-and-tube heat exchanger in which water flows in parallel pipes (eleven copper riser tubes) from the header inlet pipe to an outlet pipe on the upper side of the collector that collects the warm fluid [52].

Following an approach similar to those reported in the literature on the modelling of PVT collectors [10,30,54,55], energy balance equations were written for each layer of the PVT unit. Several assumptions were made when developing the PVT collector model; that the panel is in thermal equilibrium and the system is in quasi-steady state [30,53], that the PV cells and the absorber plate are in perfect thermal contact [51], and that a mean temperature can be assumed across the different sections of each layer [53]. A detailed list of the assumptions made as well as all the full set of equations developed to model the unit can be found in Ref. [14].

The whole PVT system considered comprises an array of 9 modules, each with a nominal electrical power rating of 250 W_p (peak installed electrical capacity) when fully covered (see Table 1), arranged in parallel in such a way that all of them can be assumed to perform identically. Hence, the complete PVT system has a nominal electrical power rating of 2.25 kW_p. Each module consists of mono-crystalline (c-Si) cells with a conversion efficiency of 15.4% at Standard Test Conditions (STC, i.e. 1000 W/m^2 and 25 °C). The temperature coefficient of the PV module (signifying a drop in performance), β_0, is 0.0053 K^{-1}. Other technical specifications are detailed in Table 1, while the optical properties, thickness, thermal conductivity and other parameters of the different layers that compose the PVT unit can be found in Herrando et al. [14]. Another quantity that should be estimated is the pumping work required to drive the closed collector cooling flow circuit. For this purpose, the recommended flow-rate provided by the PVT manufacturer is used in order to select a commercially available off-the-shelf pump that meets these specific requirements. The flow conditions and pressure drop are estimated for the different flow-rates considered and the results show that laminar fully-developed flow can be assumed in all cases. With this data, the energy consumed by the pump is calculated at each time step and subtracted from the energy generated by the PVT unit (for more details please refer to Herrando et al. [14]).

Table 1
Technical specification of the modelled PVT solar collector unit [43].

Nominal power (P_{PV})	250	W_p
Total surface area	1.62	m^2
Total aperture area	1.57	m^2
Voltage at Maximum Power Point (MPP)	30	V
Current at MPP	8.34	A
Open circuit voltage	36.9	V
Short circuit current	8.34	A
Pressure drop at the recommended flow-rate	150	mbar
Maximum operating pressure	3.5	bar
Recommended flow-rate	108	L/h
Reference PV module efficiency	15.4	%
Temperature coefficient of cell power (β_0)	−0.53	%/K
Normal Operating Cell Temperature (NOCT)	45 ± 0.2	°C
Type of solar cell	Mono-crystalline (c-Si)	

3.1.2. Water storage tank

The water contained in the storage tank accumulates the thermal energy delivered by an internal heat exchange coil that is located inside the tank. The amount of water contained in the tank remains constant because when there is a demand for hot water an equal amount of water that leaves the tank at the top is replenished by cold water (at $T_{win} = T_{sup}$) that enters the tank at the bottom. When the temperature of the water in the tank is lower than 60 °C, $T_t < 60$ °C, an auxiliary heater heats it up to this temperature before delivering the hot water to the house for consumption (Fig. 2).

It is known that the (average) daily hot-water demand of the house studied is ∼122 L (Section 3.2). Therefore, the auroSTOR 150 L provided by Vaillant [56] was selected, which is a commercial water-storage tank with a capacity of 150 L. The overall heat transfer coefficient of the heat exchanger immersed in this tank was calculated based on the geometry of the tank and the heat exchanger dimensions provided by the manufacturer. An overall heat transfer coefficient $(UA)_t$ value of 570 W/K was found, which is used in our model. As before, all the equations developed to model the unit and other parameters are detailed in Herrando et al. [14].

3.2. Reference house

To undertake the techno-economic analysis of the chosen hybrid PVT/w system, a reference house located in London was selected. According to the Department for Communities and Local Government [57], the most common type of house in London is the terraced house, with an average number of three bedrooms per house and an average of four inhabitants: two adults and two children. In addition, the floor area of an owner-occupied house it is typically around 70–89 m^2 [58], although the average roof-space available for the installation of any solar collector or panel is 15 m^2 [59].

A repetitive 'typical' (i.e. average) diurnal hot-water consumption profile as well as a daily averaged load are needed for studies such as ours [8]. The profile considered in the present paper is based on the results found in a statistical study of domestic hot-water consumption in 124 dwellings in England [60], which showed a mean household consumption of 122 L/day at a temperature of 60 °C [31,61]. In addition, the temperature of the mains cold water was taken as 10 ± 2.6 °C [62].

The electricity demand profile of an individual dwelling is strongly dependent on the number of occupants and their activities, as well as on the electrical appliances available and their associated use, and therefore it is more difficult to define [63]. In our effort, a number of different behavioural models and demand profiles were reviewed from studies undertaken in Sweden and the UK [13,63,64], from which the UK-based effort developed by the Centre for Renewable Energy Systems Technology (CREST) [63] was selected for use in our calculations. In this model, the active occupancy reflects the natural behaviour of people in their daily lives and is represented by an integer that varies pseudo-randomly throughout the day. The resulting model was validated with the electricity demand of 22 dwellings in the town of Loughborough in the East Midlands, the UK, recorded over a yearly period. A further advantage of this model is that an Excel file is available online [65], which requires three simple inputs: the number of residents in the house, the month of the year and a choice of either weekday or weekend. Once selected, the appliances of the dwelling are randomly allocated, the active occupancy model is run and finally the electricity demand is simulated considering all the previous data.

Finally, it should be considered that the geographical location of the solar system strongly affects its performance due to the variation of the solar irradiance available in a particular place. The Photovoltaic Geographical Information System (PVGIS) online tool [66] was used to provide both the daily solar irradiance and the average ambient temperature in each month (January through December) with a 15-min resolution. These data were downsampled, by simple averaging, into the format for the input that is required by our model (i.e. 30-min time intervals), as mentioned in Section 3.1.

3.3. Annual performance simulations

As explained above, the model developed herein provides diurnal electrical and thermal output profiles that represent the performance of the PVT/w system. This requires a set of inputs to be provided (solar irradiance, ambient temperature, electricity and hot-water consumption) at half-hourly time intervals. In order to fully assess the performance of the system, it is necessary to study how it performs during the different months of the year and to test also how it responds to different demand loads. Therefore, the model was run with the characteristic inputs of each month, considering the different solar irradiance inputs and household demands, and differentiating also between weekday and weekend day electricity demands (which are significantly different). The results obtained were then weighted for weekdays and weekend days in every month in order to obtain the total annual values [64].

For example, the total annual electricity consumption of the house can be evaluated as,

$$E_T = \sum_{1}^{12}\left[\frac{261}{12}\sum_{k=1}^{48}E_{wd}(k) + \frac{104}{12}\sum_{k=1}^{48}E_{we}(k)\right], \tag{1}$$

where $E_{wd}(k)$ and $E_{we}(k)$ are the electricity consumptions on a weekday and a weekend day respectively, and k represents each half hour interval for which the model was run. This equation is applied similarly to each input/output variable of the model to obtain total annual results, which are later used for the comparison of the performance of different PVT configurations.

Based on the generated electrical and thermal energy outputs of the PVT system, two additional important parameters are the percentages of the electricity and hot-water household demands that are covered by the system. The total annual values calculated from equations such as Eq. (1) are used for this purpose,

$$\mathrm{DC}_E(\%) = \frac{E_{PVT} - E_{loss}}{E_T}\cdot 100, \tag{2a}$$

$$\mathrm{DC}_{HW}(\%) = \frac{Q_{PVT}}{Q_T}\cdot 100, \tag{2b}$$

where E_{PVT} and Q_{PVT} are the *gross* electrical (directly from the PVT panel) and *net* thermal energy (for hot-water production) outputs of the PVT system, and E_{loss} is the electrical energy consumed by the pump (#4 in Fig. 2), all over a full year. In addition, E_T and Q_T are the total annual household demands in electricity and hot water. Note that E_{PVT} is related to the *net* electrical energy available *from* the PVT-supported household E_{PVTnet}, via $E_{PVTnet} = E_{PVT} - E_{loss} - E_T$, and is typically negative.

In order to compare the integrated (electricity plus heat) performance of the different configurations studied, two additional parameters are considered. These are the average percentage of demand covered (DC_{av}) and the weighted average percentage of demand covered by the PVT system throughout the year (DC_{wav}):

$$\mathrm{DC}_{av}(\%) = \frac{\mathrm{DC}_E + \mathrm{DC}_{HW}}{2}, \tag{3a}$$

$$\mathrm{DC}_{wav}(\%) = \frac{E_T\mathrm{DC}_E + Q_T\mathrm{DC}_{HW}}{E_T + Q_T}, \tag{3b}$$

which are average measures of the *combined* electrical and thermal household demands covered by the PVT.

Finally, it is desired to consider the displaced emissions and primary energy associated with the installation of the PVT system. This is done by comparing the above results with those from an equivalent reference scenario in which electricity and hot water are provided by 'conventional' means (in the absence of the PVT system). The end-user consumption of electricity and hot water in the conventional scenario differs from the household demands for natural gas from the mains and electricity from the grid. This is because, although all of the electrical demand is covered by the grid, the hot-water demand is satisfied, on average, not only by natural gas, but also by the grid via electrical heaters and heat pumps. In the present study, the end-user consumption of electrical power and hot water are converted into household gas and electricity demands by considering UK-specific data on the current uptake of electrical heaters, air- and ground-source heat pumps, boilers and their respective efficiencies or Coefficients of Performance (COPs). Based on this information, the following two expressions are obtained:

$$Q_{gas} = \frac{0.97}{0.88}\cdot Q_{aux}, \tag{4a}$$

$$E_{grid} = \left(1 + \frac{0.03}{1.5}\cdot\frac{Q_{aux}}{E_{PVTnet}}\right)\cdot E_{PVTnet}, \tag{4b}$$

where Q_{aux} and E_{PVTnet} are the heat supplied by the auxiliary heater and the electricity required to cover the demand in each case, or in other words the short-fall between the demand and the amount produced by the PVT system. These expressions are also used to calculate the CO_2 emissions incurred to cover these demands.

The following data was used to obtain the factors in the expressions in Eq. (4):

- About 3% of all boilers in the UK are electrical heaters and heat pumps, with the two systems being employed equally (about 20,000 new units per year in 2010). Air-source heat pumps are more commonly used by about a factor of 3 relative to ground-source equivalents [67].
- The average boiler efficiency is 88% [33]. This value is dominated by the vast majority of high-efficiency condensing boilers (98.9% of all new boilers).
- The typical COP of an air-source heat pump (ASHP) in the UK is 1.75 when producing hot water [68]. The typical COP of a ground-source heat pump (GSHP) in the UK is 3.16 [69].
- Thus, a value of 2 was taken as the weighted average heat pump COP ($0.75 \times 1.75 + 0.25 \times 3.16 = 2.1$, given the relative number and COP values of ASHP and GSHP from previous bullet points, assuming similar system sizes), and a value of 1.5 as an average conversion factor from electricity to heat considering electrical heaters and both types of heat pump ($0.5 \times 2.1 + 0.5 \times 0.88 = 1.5$, given the relative number and efficiency/COP values of boilers and heat pumps, assuming similar sizes).

Hence, 97% of households will have a conversion of 0.88 from fuel (gas/liquid/solid) to hot-water heating and unity for direct use of electricity, while the rest (i.e. 3%) of the households will have no gas/liquid/solid, and a conversion of 1.5 from electricity to heat and unity for direct use of electricity.

3.4. Economic assessment

The goal of this paper, going beyond technical performance, is to estimate the cost savings made possible (at the time of the undertaking of this research in 2012) by the installation of a hybrid PVT/w system compared to the costs incurred from the use of a reference system consisting of buying electricity from the grid and satisfying the hot-water demand by conventional means, which is defined as an mix of using natural-gas boilers, electrical heaters and heat pumps (according to the current average UK *status quo*; see Section 3.3). The costs incurred for conventional hot-water production are compared with the ones due to the use of the auxiliary heater needed to cover the demand that cannot be supplied by the PVT unit. Therefore the percentage of savings is,

$$C_{sHW}(\%) = \frac{C_{cHW} - C_{aux}}{C_{cHW}} \cdot 100, \tag{5}$$

where C_{sHW} refers to the percentage of cost savings due to the hot-water demand covered by the PVT system, C_{cHW} are the total running costs of the conventional system incurred to cover the total domestic hot-water demand, and C_{aux} are the total running costs of the auxiliary heater needed to cover the same demand when a PVT unit is installed.

Similarly, the cost of electricity is compared to the reduced one incurred then a PVT system is installed,

$$C_{sE}(\%) = \frac{C_{cE} - C_{PVTE}}{C_{cE}} \cdot 100, \tag{6}$$

where C_{sE} refers to the percentage of cost savings due to the electricity demand covered by the PVT system, C_{cE} are the total running costs associated with the purchase of the overall electricity demand from the grid, and C_{PVTE} are the total running costs incurred to cover the demand when a PVT unit is installed.

For $C_{PVTE} > 0$ electricity must to be bought from the grid (since C_{PVTE} is defined as a cost), while $C_{PVTE} < 0$ indicates that a net income can arise from a surplus of electricity produced by exporting to the grid. When calculating this term a differentiation is made such that when E_{PVTnet} is negative (electricity deficit) the grid electricity price is applied, whereas when this term is positive (electricity surplus) the FIT rate is applied, since it is assumed that the household will sell this surplus to the grid (see Table 2).

Table 2
Economic and environmental parameters used for the estimation of cost and emissions savings.

	Economic parameters	Value	Ref.
C_{NG}	Natural gas price (p/kW$_{th}$ h)	5.8	[70]
C_e	Electricity price (p/kW$_e$ h)	17.4	[71]
FIT	FIT for PV modules (p/kW$_e$ h)	43.3	[49]
RHI	Nominal RHI for solar thermal products (p/kW$_{th}$ h)	8.5	[50]

It is emphasised that the *net* electrical energy available from the PVT-supported household E_{PVTnet} is calculated at each time step, *after* the household's electrical consumption *and* the necessary pumping power required for the operation of the PVT system have been covered locally. When this parameter (E_{PVTnet}) is negative, the electricity deficit is bought from the grid at the grid electricity price, whereas when it is positive, the electricity surplus is sold to the grid at the FIT rate. The power consumed by the PVT circuit pump varies significantly depending on the PVT collector cooling flow-rate. The consumption amounts to 1–2% at the lower flow rates (20 L/h), with a worst-case consumption of approximately 10% of the system's annualised output when the higher flow rates (160 L/h) are used.

3.4.1. Total investment and annual running costs

The total investment cost of a PVT system comprises not only the PVT module cost but also other costs such as the water storage tank cost and the Balance of System (BOS) costs. The PVT module price also varies depending on the covering factor, as the PV laminate is an important part of the overall PVT price. As a consequence, if the area covered with PV is smaller, the cost is expected to decrease. In order to consider this variation, the following assumptions are made:

- The PVT module considered is the ENERGIES-SOL PVT unit, with a nominal electrical power rating of 250 W$_P$ and 1.624 m^2 of total surface area (see Table 1).
- The price of the PVT module is £480 [43].
- The price of the PV part is considered to be £0.92/W$_P$ for a c-Si module of 250W$_P$ (according to Samsung prices [72]).

Consequently, the price of the PV part per surface area is estimated as £142/m^2 and the percentage of the total price that corresponds to the PV part can be estimated from:

$$\frac{\frac{£0.92}{W_p} \cdot 250\ W_p}{£480} \cdot 100 = 47.9\%. \tag{7}$$

Based on the collector and overall system defined earlier, it is estimated that the installation costs are reduced by about 10% compared to the installation of both PV and solar collector systems [26,27], where the costs of each of these is around £800. Table 3 summarises the investment cost breakdown for the fully covered PV case in which the covering factor is $P = 1.0$.

The additional costs of the inverter, metal structure and wires, and other small components required are based on the costs found relating to a 3 kW$_P$ (electrical) residential PV system. Also, in order to estimate the costs of the collector fluid circuit, prices given by Vaillant [56] for a complete flat-plate solar collector kit are considered, from which the flat-plate collector cost as well as the metal structure cost are excluded since they are already included in the

Table 3
Price breakdown for a solar system featuring a hybrid PVT collector rated to 2.25 kW_P (electrical) with complete coverage of the collector with PV, i.e. $P = 1$, and a 150 L hot water storage tank. The stated values are for $P = 1$; these were recalculated for different values of P where relevant in this study.

Concept	Price	Unit	Comments
Single PVT panel ($P = 1$; 250 W_P)	480	£/panel	[43]
Total PVT panels (× 9)	4320	£	£480/panel × 9 panels
Inverter	640	£	[73]
Metal structure	270	£	Estimated from the price
Wires and small components	490	£	breakdown of a PV system
Collector closed-loop set	800	£	auroTHERM kit [56]
Water storage tank	820	£	auroSTOR [56]
Installation costs	1440	£	Estimated[a]
Total upfront cost (C_0)	8780	£	

[a] Based on estimated installation costs of equivalent separate PV and solar-thermal collector systems of around £800 each, and assuming that the total cost of a hybrid system will be lower by about 10% compared to the installation of the two separate systems [26,27].

price of the PVT unit. A cost for the specific water storage tank considered was also found directly from price lists.

The total annual running costs (A_i) incurred are the sum of the running costs due to electricity (C_{PVTE}) and hot-water production (C_{aux}), as well as the operation and maintenance costs ($C_{O\&M}$), which are estimated to be 1% per year [8]. Hence:

$$A_i = C_{PVTE} + C_{aux} + C_{O\&M}. \tag{8}$$

Finally, the investment costs of a PV-only system were also estimated in order to allow comparisons between the PVT systems studied here and a PV-only equivalent. In performing this exercise, it was assumed that the total electrical capacity of the two systems was the same (2.25 kW_P), and that both used c-Si PV cells [72]. A summary of the total investment costs is given in Table 4. Similarly to Eq. (8) that relates to the PVT system, the total annual running costs (A_i) incurred in the PV-only case are the sum of the running costs due to electricity (C_{PVE}) and hot-water (C_{cHW}) production, as well as the operation and maintenance costs ($C_{O\&M}$). However, in this case, as hot water is not produced, the total amount of energy required to heat the overall hot-water demand should be purchased. Hence:

$$A_i = C_{PVE} + C_{cHW} + C_{O\&M}. \tag{9}$$

The PV-only solution is envisaged here as being retrofitted to a household with a pre-existing boiler, so no additional investment costs are associated with the conventional scenario.

Table 4
Price breakdown for a PV-only system with a power output rating of 2.25 kW_P (electrical).

Concept	Price	Unit	Comments
Single PV panel (250 W_P)	230	£/panel	[72]
Total PV panels (× 9)	2070	£	£230/panel × 9 panels
Inverter	640	£	[25]
Metal structure	270	£	Estimated from the price
Wires and small components	490	£	breakdown of a PV system
Installation costs	800	£	
Total upfront cost (C_0)	4270	£	

3.4.2. Payback and inflation/market discount rates

In order to compare the economic proposition offered by different alternative systems and to thus decide which one is the best solution in terms of lower payback period, both the upfront investment costs and the running costs given above should be considered. However, these cannot be simply added because: (i) money in the present is worth more than the same sum in the future, since an investment in the present can generate a profit in the future at some compounding interest and (ii) the value of money decreases due to inflation [74]. Inflation and discount rates were also considered in the present economic analysis in an effort to take into account the time value of money. The present worth (PW_n) of a total upfront cost (C_0) at the end of year n can be calculated assuming a discount rate d and an inflation rate i [8]:

$$PW_n = \frac{C_0(1+i)^{n-1}}{(1+d)^n}. \tag{10}$$

Similarly, the annual costs can be estimated, converted into present worth values and added to obtain the Life Cycle Savings (LCS) [8]:

$$PW_{LCS} = \sum_{n=1}^{N} \frac{A_i(1+i)^{n-1}}{(1+d)^n}. \tag{11}$$

Therefore, the cumulative costs each year will be the sum of the costs of previous years (including the investment cost) plus the costs incurred that year. All of them converted into present worth values.

To obtain the Discounted Payback Period (DPB) of the PVT system, the cumulative costs throughout the years are compared with the costs that would have been incurred if the electrical and hot-water demands had been supplied by the conventional system, as explained previously. The year in which both cumulative costs curves intersect is the year in which the same amount of money has been spent in both cases, while taking into account the investment and running costs of the PVT system. If the PVT system is run beyond this point, there will be net costs savings in the case of the PVT solution (e.g. see Figs. 5–7).

The above-mentioned assessment requires knowledge of the inflation and the discount rates, while noting that the conventional system has a different discount rate to that of the PVT system, the latter being higher than the former given the increased investment risk that is associated with a renewable energy project. A discount rate, d_c, which is equal to the interest rate given by commercial banks in the UK was taken for the conventional system, which at the time of the present study was about 2.5%. A higher discount rate of 4% is also considered in an effort to study the influence of this parameter on the results. On the other hand, there is some discrepancy in the discount rate values, d, employed in literature for PVT systems; values range from 5% [16] to 8% [74] and even 10% [47,75]. The decision was made to consider this range of values in the form of a sensitivity analysis aimed at uncovering their influence on the results.

Finally, regarding the inflation rate, i, the Consumer Price Index (CPI) was estimated to be 2.6% at the time of the study [76], but it is believed that the Retail Price Index (RPI), estimated as 3.2%, is a more appropriate value to use as it includes housing costs such as mortgage interest payments and council tax. Further, as the inflation rate is expected to vary and historical values show higher rates, two more values, 4.5% and 6%, were considered as in the approach above for the discount rate.

3.4.3. Further economic parameters

Beyond the discount payback period, a few additional economic parameters are important when it comes to exploring various PVT configurations, and how these compare to alternative solutions.

These are the Net Present Value (NPV), the total-energy Levelised Production Cost (LPC) and the Levelised Coverage Cost (LCC), all of which are also included in the present paper, calculated for two different system lifetimes, $n = 20$ years [8] and $n = 25$ years [47], and for the three different discount rates specified above.

The NPV represents the total cumulative cost of the system over its lifetime, translated to the present. The LPC represents the "cost of energy" of the system, that is, the average unit cost of total-energy production, assuming constant outputs. In this case both the hot water and electrical energy outputs are included, even though it is known that the thermal output is a lower-grade energy form and thus less valuable than the electrical output. Additionally, LCC_E, LCC_{HW}, LCC_{av} and LCC_{wav} stand for the Levelised Coverage Cost per % of electrical, hot water, average and weighted average demands covered, respectively. For example:

$$\mathrm{LCC}_E = \frac{L(\text{£/year})}{\mathrm{DC}_E(\%/\text{year})}, \tag{12}$$

where L represents the levelised cost of energy (£/year) and DC_E is the percentage of electricity demand covered by the PVT system over the course of a year (%/year).

3.5. Techno-economic analysis

Numerous parameters are required to define (and design) a PVT unit and the system within which it is placed and operated, while several additional variables can be tuned to modify and optimise its performance. However, as discussed in Herrando et al. [14], two parameters are expected to play a significant role in determining the performance of a PVT system. These are the cooling water flow-rate through the collector (V_P), and the covering factor of the collector with PV (P). One of the objectives of the present paper is to select the values of these parameters that can provide improved results in terms of the covered hot-water and electricity demands, whilst maximising the running-cost savings in our specific scenario. Other parameters were fixed based on suggestions and other information found in literature.

Based on the approach taken in Herrando et al. [14], the following approach has been followed here:

1. Parametric analyses are carried out over a full year, to study:
   (a) Variations of P from 0.2 to 1.0 in steps of 0.2 for four different collector flow-rates: V_P = 20 L/h, 80 L/h and 160 L/h.
   (b) Variations of V_P from 20 L/h to 200 L/h in steps of 20 L/h for three different collector PV covering factors: P = 0.6, 0.8 and 1.0.
2. Five configurations are selected in order to study in more detail their performance in terms of running-cost savings in the different months throughout the year. A complete economic assessment is also undertaken to compare the results with those of a PV-only system with the same peak rating/installed capacity. This step includes (electricity) FIT incentives only.
3. Following this step, the effect of the implementation of a nominal (thermal) RHI on the economics of these systems is considered as well as the implementation of a modified (thermal) RHPP scheme. This incentive, referred to as the 'augmented' RHPP (a-RHPP), is an amount equal to the total (nominal) RHI paid over a 20-year lifetime, but given as a one-off voucher at the beginning of the system's lifetime, assuming that the thermal output of the system remains constant over the 20 years.
4. Finally, an analysis is performed to estimate the required incentivisation level (termed here 'optimum' a-RPHH, or a-RHPP*) that would make the PVT systems competitive with the PV-only equivalent system in terms of payback; that is, to make the DPB of both systems equal.

4. Results and discussion

Firstly, in Section 4.1, the main findings from a parametric analysis in which the PV covering factor and cooling flow-rate (P, V_P) were varied are summarised; this includes the running-cost savings of the PVT systems. The goal of these analyses is to identify values that optimise the overall performance of the system while maximising cost savings. Following this, five PVT system configurations with appropriately chosen values of P and V_P are selected in order to study in more detail their performance in terms of running-cost savings over the different months of the year (Section 4.2), after which a complete economic assessment is also undertaken (Section 4.3). The assessment consists of two main steps: (i) Sections 4.3.1–4.3.3 consider the role of inflation and market discount rates while comparing the economic proposition of the selected PVT configurations amongst each other and also to results from an equivalent PV-only system with the same peak rating/installed capacity in the presence of incentives relating to the electrical output only (i.e. FITs); and then (ii) Section 4.3.4 proceeds to include the effects of the implementation of incentives relating to the thermal output (i.e. RHI, RHPPs) on the economics of these systems. The ultimate goal of this study is to identify the most promising PVT system configurations and to examine the techno-economic potential of such a system compared to alternatives.

4.1. Diurnal parametric analysis

The results in Herrando et al. [14] showed that the electrical output of the PVT system, and hence also the covered percentage of the household's electrical demand, was not notably affected by the collector cooling flow-rate V_P, whereas the covered hot-water demand was significantly influenced by this parameter, decreasing at higher collector flow-rates (Fig. 3). Conversely, the electrical output of the PVT system increased significantly with the increase in P due to the larger surface area of PV modules, as expected. However, as the PV module area increased, there was less absorber plate area directly exposed to the solar irradiance (which has higher absorptivity than the PV laminate), so the thermal energy transferred to the water flowing through the collector decreased, diminishing the production of hot water (and the demand covered). Consequently, Herrando et al. [14] concluded that a covering factor of 0.8–1.0 and the use of low collector flow-rates (between 20 and 80 L/h) were most appropriate in terms of a balanced coverage of the two energy demands, as well as overall CO_2 emissions savings.

The running-cost savings obtained in the present effort (Fig. 4) show similar trends to those above: the hot-water running costs increase (and the savings decrease) at higher collector flow-rates V_P, due to the decreased thermal energy transferred from the collector to the hot-water storage tank, thus giving rise to a requirement for additional auxiliary heating. Conversely, the electrical running costs (and savings thereof) are not significantly influenced by changes to V_P, in alignment with the electrical output from the PVT unit.

One should bear in mind that the electricity costs have a greater influence on the total PVT system costs compared to those associated with hot water, because of the higher cost of electricity (per unit energy). Consequently, the total running-cost savings *increase* slightly despite the fact that the hot-water running costs decrease at higher collector flow-rates. On the other hand, the hot-water running-cost savings are not notably affected by changes to the covering factor, while the electrical running-cost savings as well as the total running-cost savings increase significantly as the covering factor increases. This is due to the substantial price differential between the purchase of electricity from the grid and the FIT

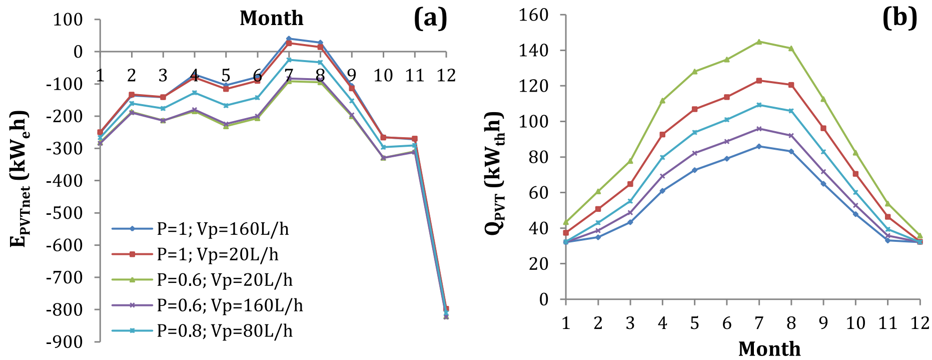

Fig. 3. (a) Net electrical energy imported/exported (−ve/+ve) by the house, and (b) thermal energy produced by the hybrid PVT collector, for each month of the year and for the five selected PVT configurations. Legend relates to both plots. Reproduced from Herrando et al. [14].

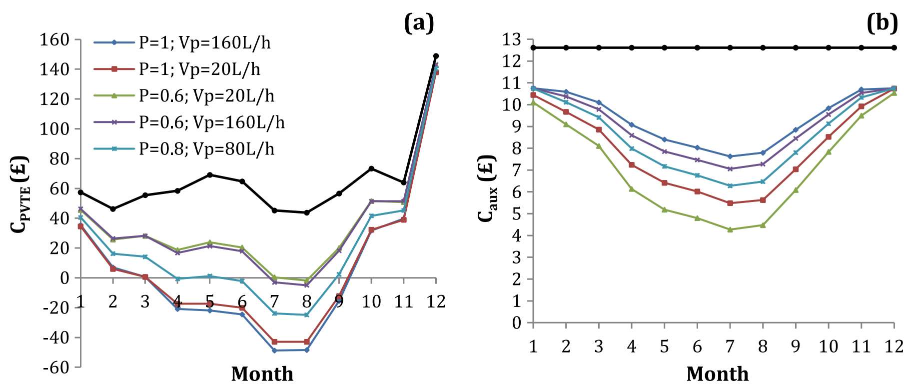

Fig. 4. Monthly running costs associated with (a) electricity and (b) hot water consumption, over the course of the year. Legend relates to both plots. The highest line (with circles) in each sub-plot represents the conventional costs required to cover the entire household demands in electricity and hot water. It is assumed that the volume of the hot water storage tank is larger than the average daily consumption.

received when a surplus of electricity is sold to the grid, which makes the system more profitable when the area covered by PV increases. Therefore, it can be concluded that the collector flow-rate does not have a notable influence on the running-cost savings, and that it is more favourable to have a high covering factor.

4.2. Annual results for selected PVT configurations

The results of the parametric analysis in Section 4.1 above show that low collector flow-rates, V_P, and high covering factors, P, are recommended to maximise the electrical and thermal outputs of the PVT system over a full year in our particular UK-based scenario, while at the same time increasing the running-cost savings. In order to gain further insight into the detailed operation and performance of the PVT system throughout the year, five specific combinations of collector flow-rates and covering factors are selected:

- System featuring a high electrical performance unit design, operated for a high electrical output: Covering factor $P = 1.0$ and collector flow-rate $V_P = 160$ L/h.
- System featuring a high electrical performance unit design, operated for a high thermal output: Covering factor $P = 1.0$ and collector flow-rate $V_P = 20$ L/h.
- System featuring a high thermal performance unit design, operated for a high thermal output: Covering factor $P = 0.6$ and collector flow-rate $V_P = 20$ L/h.
- System featuring a high thermal performance unit design, operated for a high electrical output: Covering factor $P = 0.6$ and collector flow-rate $V_P = 160$ L/h.
- Intermediate solution system: Covering factor $P = 0.8$ and collector flow-rate $V_P = 80$ L/h.

The first combination was chosen to represent a system with a PVT unit that exhibits the best electrical performance (high P), operated so as to maximise its electrical output (high V_P), and the second combination is the same system operated to maximise its thermal output (low V_P). Similarly, the third combination represents a system with a PVT unit that exhibits the best thermal performance (low P), operated so as to maximise its electrical output (high V_P), and the fourth is the same system operated to maximise its electrical output (low V_P). The final combination is an intermediate solution in terms of design and operation.

Fig. 3(a) shows the net electrical generation/availability of our PVT-supported household, which varies significantly from month to month. This results from the higher electricity demand in winter months when the electrical output of the PVT system is also lower, thus requiring more electricity to be bought from the grid (leading to negative values of E_{PVTnet}). It should be noted that for PVT units with $P < 1$ the net electrical energy is always negative, which means that electricity should be imported from the grid throughout the year, while for $P = 1.0$ the total net monthly electricity generation is positive in summer months when the electricity surplus can be exported to the grid, providing an income. In contrast, there is little difference between the net electrical energy imported or exported from/to the PVT-supported household when different flow-rates are tested.

In terms of thermal energy (hot-water) production both the covering factor P and the collector flow-rate V_P influence the output of the system, as shown in Fig. 3(b). The best results throughout the year are obtained by a PVT system with a covering factor of 0.6 and a collector flow-rate of 20 L/h, whereas the worst results are obtained when a covering factor of 1 and a collector flow-rate of 160 L/h are used. Hence, these results suggest that the very slight improvement in electrical output at higher flow-rates observed in relation to Fig. 3(a) may not outweigh the decrease in hot-water production observed in Fig. 3(b).

The total running costs incurred per month in order to cover the household's electricity demand (Fig. 4(a)) vary significantly depending on the month, for two reasons: (i) the electricity demand of the household varies depending on the month of the year; and (ii) the net electrical energy produced per month also varies notably. Negative costs in a particular month correspond to an income, as there is an energy surplus that can be sold to the grid, while positive costs reflect an energy deficit that should be covered from the grid. Therefore, PVT units with a unity covering factor, $P = 1.0$, are suggested for increased income compared to the units with $P < 1$.

Regarding the running costs associated with the auxiliary heating needed to cover the hot-water demand (Fig. 4(b)), the annual variation is more regular, with lower costs incurred in summer months due to the higher solar irradiance and increased thermal output from the PVT system. These costs also vary for the different cases considered, with $P < 1$ and lower flow-rates incurring lower hot-water running costs. However, the extent of variation of these costs (maximum difference around £1 per month) is much smaller than the range of variation of electrical running costs (maximum difference around £20 per month), which establishes the cost of electrical as being of far greater importance when considering the economic proposition of the PTV system. It is noted, with respect to both the electrical and hot-water costs, that a significant amount of the total costs are covered by the PVT configurations.

4.3. Economic assessment

4.3.1. Inflation and market discount rates

In the first economic sensitivity analysis in Fig. 5, the discount rates are kept constant and the inflation rate is varied (from $i = 3\%$ to 6%) for both the conventional system and a PVT configuration with $P = 1.0$ and $V_P = 20$ L/h. (Similar results are found for the rest of studied configurations.) The results show that the inflation rate significantly affects the cumulative costs of the conventional system, which deviate by up to ±10% from the costs for the $i = 4.5\%$ inflation-rate case for the first 15 years, diverging to ±14% in 20 years, whereas it does not notably influence the cumulative costs of the PVT system, which remain within ±3.5% over 20 years. As expected the higher the inflation rate, the higher the cumulative costs in both cases, however, the conventional costs increase faster than the PVT costs leading to a reduced discounted payback period (DPB) of the PVT system. The most beneficial

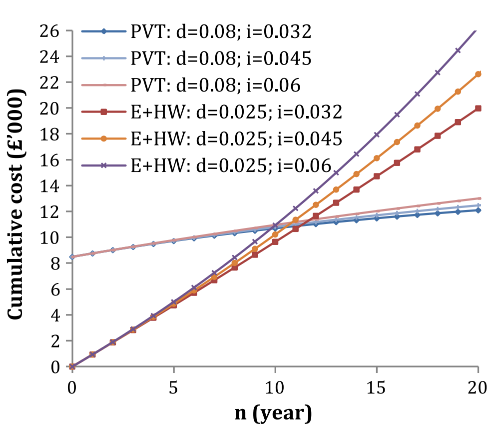

Fig. 5. Comparison of the cumulative cost of the PVT system with a discount rate of $d = 0.08$ to that of the conventional scenario with a discount of $d_c = 0.025$, for different inflation rates (i).

scenario from the point of view of PVT technology occurs when the inflation rate is at $i = 6\%$, with a corresponding DPB of 10 years. When the inflation rate is low (here, $i = 3.2\%$) and more representative of present values, the DPB becomes 12 years.

In the second analysis, the inflation rate is kept constant at $i = 3.2\%$ (Fig. 6(a)) and at 6% (Fig. 6(b)) while we study the influence on the cumulative system costs of variations to the discount rates. In both cases the cumulative costs increase as the discount rates increase, and once again the conventional system costs are more sensitive to changes in the discount rate compared to the PVT system. The DPB varies from 10 to 13 years when the inflation rate is $i = 3.2\%$, and from 10 to 11 years when the inflation rate is $i = 6\%$. In both cases the more promising PVT scenario occurs for a PVT system discount rate of $d = 10\%$ and a conventional system discount rate of $d_c = 2.5\%$, and the worst for a PVT system discount rate of $d = 5\%$ and a conventional system rate of $d_c = 4\%$. This reflects the fact that the higher the discount rate is, the less valuable money in the future is, and the slower the cumulative costs will increase in time. Therefore high discount rates are beneficial for the PVT system, whereas low discount rates make the conventional system increasingly desirable, since it is less profitable to invest the money in a commercial bank.

4.3.2. Comparison of PVT configurations

To compare the economics of the different PVT system configurations considered here, the inflation rate is kept constant at $i = 3.2\%$ and the discount rate estimated for the conventional system is also kept constant at $d_c = 2.5\%$, while three PVT discount rates ($d = 5\%$, 8%, 10%) and two different PVT system lifetimes ($n = 20$, 25 years) are analysed. The results for all cases are shown in Table 5, where the best solution appears highlighted as bold and italic in each parameter/row. The $P = 1.0$ and $V_P = 20$ L/h system appears as particularly promising, especially at high discount rates. Still, similar trends are found for the different PVT discount rates, therefore from now onwards, unless otherwise stated, a discount rate of $d = 8\%$ will be used for the PVT systems considered as it provides a representative intermediate DPB value.

Fig. 7 shows that the cumulative cost curves of the two fully covered PVT configurations (with a covering $P = 1.0$) overlap, and that these have a lower DPB period (close to 11 years) than the rest of the PVT systems with $P < 1$. Furthermore, Fig. 8 shows that the Net Present Value (NPV) of the fully covered configurations is also lower, which means that the overall costs incurred after a 20-year life with the partially uncovered options are higher. This is an interesting result in light of the lower investment costs of the PVT configurations with $P < 1.0$. It suggests that the higher initial costs of fully covering the PVT collector are overcome readily in terms of NPV and DPB. The two fully covered ($P = 1.0$) collector configurations (with extreme low $V_P = 20$ L/h, and high $V_P = 160$ L/h) show very close NPV and DPB results; evidently, these economic parameters are strongly determined by the electrical output of the collector and not sensitive to the choice of cooling flow rate selected for the system. This can also be seen in Fig. 7 where the costs of the fully covered solutions become the lowest of all PVT options after ∼7 years (see intersection point), after which point they have offset their higher investment costs at $n = 1$.

Similar results are found when the levelised costs, LPC (Fig. 9(a)) and the LCC_{wav} (Fig. 9(b)), are considered, again for similar reasons as above, i.e. due to the significantly lower electricity production when the PVT collector is only partially covered, which is not outweighed by the higher hot-water production (see also Table 5). The fully covered ($P = 1.0$) and low ($V_p = 20$ L/h) flow-rate configuration attains the lowest LPC and LCC_{wav} (in Fig. 9) due to the combined highest electrical and hot-water outputs. The results from the other PVT configurations lead to similar observations, with the intermediate case ($P = 0.8$, $V_p = 80$ L/h) giving slightly better

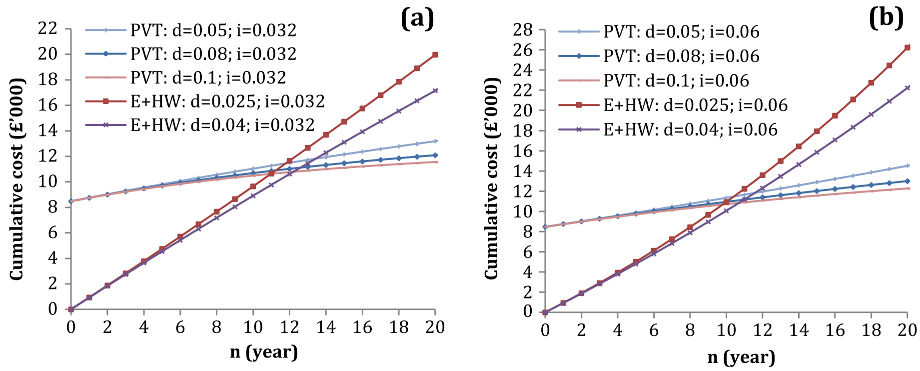

Fig. 6. Comparison of the cumulative cost of the PVT system to that of the conventional scenario with an inflation rate of: (a) $i = 0.032$ and (b) $i = 0.06$, for different discount rates (d).

results than the configurations with $P = 0.6$, due to lower annual costs (see Table 5) and lower LCC_E, given the higher levels of electricity production.

4.3.3. Comparison with a PV-only system

In order to compare the economics of the PVT configurations with those from a PV-only equivalent system (same peak rating/installed capacity), the inflation rate is kept constant at $i = 3.2\%$, the discount rate estimated for the conventional system is kept constant at $d_c = 2.5\%$, and the discount rates for the PVT and PV-only systems considered are both set to $d = 8\%$. Fig. 10 shows that due to the significantly lower investment cost of the PV-only system, the payback period of this option is lower, specifically at 6.8 years (see Fig. 10(b)), compared to the 11–12 years of the PVT systems (see Fig. 10(a)). It is possible to observe that the slope of the costs the PV system is very similar to that for the PVT configuration with $P = 1.0$ and $V_P = 160$ L/h, as expected, since in this case the electricity production of the two systems is very similar, and the hot-water production from the PVT alternative is at its lowest (see Table 5).

Fig. 11 shows the fractions of the household demands covered from the different PVT configurations and the PV-only system, taken from Herrando et al. [14]. It can be seen that the electrical output and hence electrical demand covered by the PVT systems with a covering factor of unity are higher than that of the PV-only system, albeit only slightly, while a low collector flow-rate is preferred since it also allows the system to cover a significant fraction of the hot-water demand. About one-half of the electricity and a little more than one-third of the hot-water (50.7% and 35.6%, respectively; Table 5) can be covered by the $P = 1.0$ and $V_p = 20$ L/h PVT system. Hence, purely in terms of performance, it can be concluded that PVT systems are better than PV-only systems in terms of catering to the combined household energy demands. At the same time, Fig. 9 shows that in terms of LPC as well as LCC_{wav}, PVT systems can be on par or offer a slightly improved alternative (again only slightly) than PV-only systems. These results reflect the fact that these economic parameters consider both outputs of the solar technologies, even though the PV-only system has no thermal output and consequently a zero hot-water output and demand coverage.

As a consequence, the above findings in this paper lead to the conclusion that although the total upfront cost of PV-only systems is significantly lower than for PVT systems, when the total coverage of domestic energy demands as well as the total energy production are considered, PVT systems present a better alternative in terms of distributed energy generation, efficiency and emissions displacement. A follow-up conclusion that can be drawn from this observation is that in order to make PVT systems an attractive investment and thus harness their potential, *at least relative to PV*, policy measures are needed to lower their high upfront costs by means of investment subsidies, for example with a higher voucher than the actual Renewable Heat Premium Payment (RHPP) applicable to solar-thermal systems (which is £300).

4.3.4. Effect of heat incentives

Results up to this point were based on the availability of incentives relating to the electrical output of the PVT systems under consideration only (i.e. FITs); from this point onwards we proceed to also include incentives relating to the thermal output of these PVT systems. As suggested in the previous section, policy measures are necessary if it is desired to incentivise the installation of PVT systems. In Section 2.4, UK Government support was reviewed, showing that relevant financial support can take the form of a RHI, consisting of regular payments, or RHPP, comprising a one-off payment at the point of purchase. This section studies the influence that these incentives have on the economics of the PVT systems studied in order to understand to what extent this support can help to accelerate the uptake of this technology.

Earlier it was concluded that the PVT configuration that gives the best results is the one with a covering factor of unity and a low collector flow-rate of 20 L/h, therefore this configuration is selected for further study. In order to gain more insight into the influence of the thermal output on the overall economics of the system, the following configurations are also considered:

- System featuring a high electrical performance unit design, operated for a high electrical output: Covering factor $P = 1.0$ and collector flow-rate $V_P = 160$ L/h.
- System featuring a high thermal performance unit design, operated for a high thermal output: Covering factor $P = 0.6$ and collector flow-rate $V_P = 20$ L/h.
- Intermediate solution system: Covering factor $P = 0.8$ and collector flow-rate $V_P = 80$ L/h.

These systems are also compared with the PV-only system.

Fig. 12(a) shows that the implementation of a nominal RHI at a rate of 8.5 p/kW h notably decreases the difference between the cumulative costs of the PVT and PV-only systems over time (compared to Fig. 10), as expected thanks to the payments for the delivery of the thermal output (see Table 6). It can also be observed that the cumulative costs of the two fully covered ($P = 1.0$) PVT systems now diverge slightly over time; this due to the higher thermal output of the configuration with lower flow-rate, which provides a higher annual revenue stream. The PVT DPB periods are now 10–11 years, with PV still at 6.8 years.

To complement the above study, a second mechanism of implementing the RHI has been considered. As noted previously, the

Table 5
Summary of the economic assessment for the different PVT configurations and the PV-only system studied for three different values of the discount rate. The best solution in each row corresponding to a particular parameter/category appears highlighted (bold and italic).

			$P = 1;\ V_P = 160$ L/h			$P = 1;\ V_P = 20$ L/h			$P = 0.6;\ V_P = 20$ L/h			$P = 0.6;\ V_P = 160$ L/h			$P = 0.8;\ V_P = 80$ L/h			PV-only system		
E_{PVT} (kW_eh/year)				***2390***			2290			1360			1430			1880			2190	
Q_{PVT} ($kW_{th}h$/year)				670			960			***1130***			740			840			0	
DC_E (%)				***51.8***			50.7			30.0			30.6			41.2			48.7	
DC_{HW} (%)				23.3			35.6			***42.0***			28.4			32.0			0.0	
DC_{wav} (%)				41.3			***45.2***			34.4			29.8			37.8			30.9	
DC_{av} (%)				37.5			***43.2***			36.0			29.5			36.6			24.4	
C_0 (£)				8480			8480			6750			6750			7620			***4270***	
A_i (£/year)				***283***			290			592			605			443			345	
Discount rate (d)			0.05	0.08	0.10	0.05	0.08	0.10	0.05	0.08	0.10	0.05	0.08	0.10	0.05	0.08	0.10	0.05	0.08	0.10
DPB (year)			11.7	11.4	10.9	11.8	11.2	11.0	14.2	12.4	11.7	14.5	12.6	11.8	12.9	11.8	11.3	*6.9*	*6.8*	*6.7*
NPV (£'000)	n	20	13.1	12.0	11.5	13.2	12.1	11.6	16.4	14.1	13.0	16.6	14.3	13.2	14.8	13.1	12.3	*9.9*	*8.6*	*7.9*
	n	25	14.0	12.5	11.8	14.1	12.6	11.9	17.9	15.1	13.7	18.6	15.3	13.9	16.3	13.9	12.8	*11.0*	*9.2*	*8.3*
L (£'000/year)	n	20	1.05	1.22	1.35	1.06	1.23	1.36	1.31	1.44	1.53	1.33	1.45	1.55	1.19	1.34	1.45	***0.79***	***0.87***	***0.93***
	n	25	0.99	1.17	1.30	1.00	1.18	1.31	1.27	1.42	1.51	1.32	1.43	1.53	1.15	1.30	1.41	***0.78***	***0.86***	***0.92***
LPC (p/kW h)	n	20	34.3	39.9	44.0	***32.6***	***37.9***	***41.8***	52.9	58.0	61.7	61.4	67.1	71.3	43.9	49.3	53.4	36.1	39.8	42.4
	n	25	32.4	38.2	42.5	***30.9***	***36.3***	***40.3***	51.3	57.1	60.8	60.7	66.2	70.3	42.6	48.0	52.1	35.6	39.1	41.8
LCC_E (£'000/DC_E)	n	20	2.03	2.36	2.60	2.08	2.43	2.67	4.38	4.80	5.11	4.35	4.75	5.05	2.89	3.25	3.52	*1.62*	*1.79*	*1.91*
	n	25	1.92	2.26	2.51	1.98	2.32	2.58	4.25	4.73	5.04	4.30	4.68	4.98	2.80	3.16	3.43	*1.60*	*1.76*	*1.88*
LCC_{HW} (£'000/DC_{HW})	n	20	4.50	5.25	5.79	***2.97***	***3.46***	***3.81***	3.13	3.43	3.65	4.69	5.13	5.45	3.72	4.18	4.52	–	–	–
	n	25	4.26	5.02	5.58	***2.82***	***3.31***	***3.68***	3.03	3.38	3.59	4.64	5.06	5.38	3.61	4.07	4.41	–	–	–
LCC_{wav} (£'000/DC_{wav})	n	20	2.54	2.96	3.26	***2.34***	***2.72***	***3.00***	3.82	4.18	4.45	4.47	4.88	5.19	3.15	3.54	3.83	2.57	2.83	3.02
	n	25	2.40	2.83	3.15	***2.22***	***2.61***	***2.90***	3.70	4.12	4.39	4.42	4.82	5.12	3.05	3.44	3.74	2.53	2.78	2.97
LCC_{av} (£'000/DC_{av})	n	20	2.80	3.26	3.59	***2.45***	***2.85***	***3.14***	3.65	4.00	4.26	4.51	4.93	5.24	3.25	3.66	3.96	3.25	3.58	3.82
	n	25	2.65	3.12	3.46	***2.32***	***2.73***	***3.03***	3.54	3.94	4.19	4.46	4.86	5.17	3.16	3.56	3.86	3.20	3.52	3.76

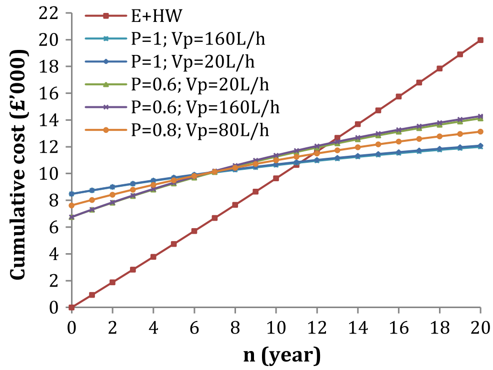

Fig. 7. Comparison of the cumulative costs of the different PVT configurations studied with a discount rate of $d = 0.08$, to that of the conventional scenario (electricity + hot water costs (squares)) with a discount rate of $d_c = 0.025$. An inflation rate of $i = 0.032$ is used throughout.

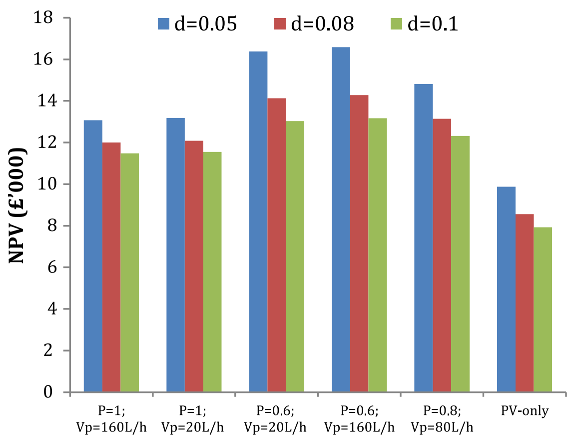

Fig. 8. Net Present Value (NPV) of the different PVT configurations studied for three different discount rates and a system lifetime of 20 years.

RHPP previously applicable to solar-thermal systems consisted of a £300 voucher for the installation of solar-thermal products in any household in England, Scotland and Wales. The results found in the present paper have shown that this payment is insufficient to incentivise PVT systems, since these systems are significantly more expensive than solar collectors and the voucher covers an almost negligible fraction of their upfront costs. We may, however, consider an alternative incentivisation scheme, which we refer to as the 'augmented' RHPP (a-RHPP). This scheme amounts to the same total support as the RHI considered previously, but is given to a household that installs a PVT system as a one-off voucher at the time of installation (i.e. the beginning of a system's lifetime), assuming that the annual thermal output of the system remains constant over the years and a lifetime of 20 years. In this case, the total investment cost of the PVT configurations studied decreases depending on their thermal output (see Table 7). The a-RHPP varies between £1200 (for $P = 1$; $V_p = 160$ L/h) and £2000 (for $P = 0.6$; $V_p = 20$ L/h), or 14% and 30% of the upfront cost of the system. For the PVT configuration selected previously as the most appropriate ($P = 1.0$; $V_P = 20$ L/h) it amounts to £1700, or 19% of the upfront cost of the system.

Fig. 12(b) shows that the a-RHPP can act to reduce further the difference between the cumulative costs of the PVT and the PV-only systems, especially in the early years of the project due to the lower investment costs. It is possible to observe that with this proposed incentive the PVT systems with high hot-water production are significantly more favoured, achieving a DPB close to 9 years, which is slightly lower than the configuration selected previously as the most appropriate ($P = 1.0$ and $V_P = 20$ L/h).

In summary, Fig. 13 and Table 8 show the results in terms of the DPB period of the PVT configurations studied and of the PV-only system for the three case studies considered: (i) FIT-only support without heat incentives, (ii) the additional introduction of a nominal RHI; and (iii) the additional introduction of an augmented RHPP. The results here show that the best economic scenario for PVT systems is the latter option, which lowers their DPB down to being 2 years longer than that of PV-only systems.

One final analysis was undertaken in an attempt to estimate the voucher amount that should be given at the beginning of a PVT system's lifetime to make these systems competitive with PV in terms of payback. This hypothetical incentive is called 'optimum' a-RHPP (a-RHPP*). Fig. 14 and Table 9 show the results of this analysis for the PVT configurations studied. Fig. 14(a) shows that, for the PVT system with $P = 1.0$ and $V_P = 20$ L/h, it would be necessary to give a minimum voucher of £4120, allowing a 47% decrease in its upfront cost, to have the same DPB period as a PV-only system (6.8 years). This voucher payment is 2.4 times larger than the a-RHPP (£1700), and hence also by the same factor compared to the total RHI paid to the household over this system's 20-year lifetime (based on 8.5 p/kW h). However, it is important to highlight that thereafter the cumulative costs of the PVT system are lower than those of the PV system, which means increased savings throughout the system's lifetime. Another conclusion that can be

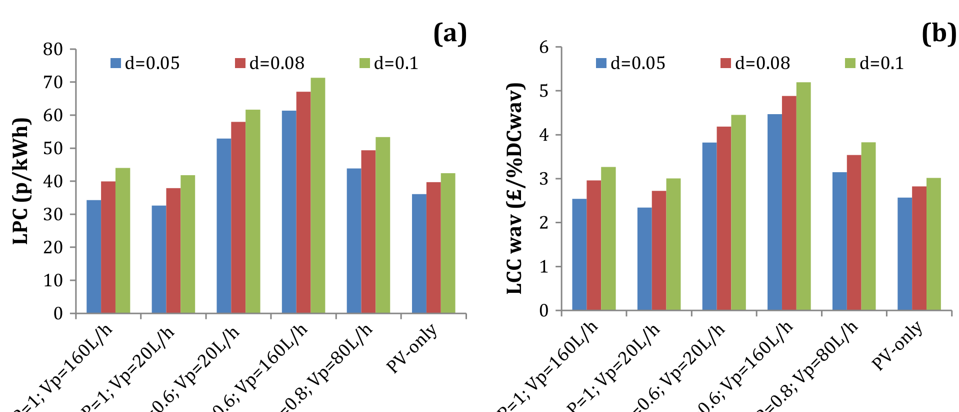

Fig. 9. (a) Levelised Production Cost (LPC) and (b) weighted average Levelised Coverage Cost (LCC) of the different PVT configurations studied for three different discount rates and a system lifetime of 20 years.

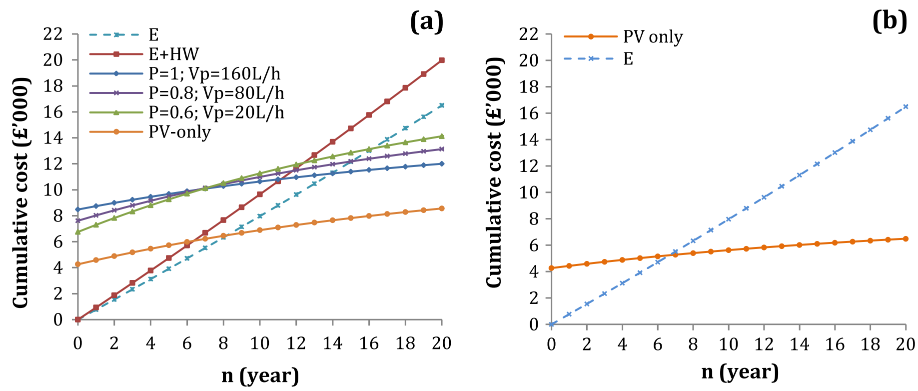

Fig. 10. Comparison of the cumulative costs of: (a) the different PVT configurations studied and (b) the PV-only system with a discount rate of $d = 0.08$. Also, showing the costs of the equivalent conventional scenarios in each case with a discount rate of $d_c = 0.025$; in (a) this includes the costs of electricity + hot water (squares), while in (b) it only includes electricity costs (crosses). An inflation rate of $i = 0.032$ is used throughout.

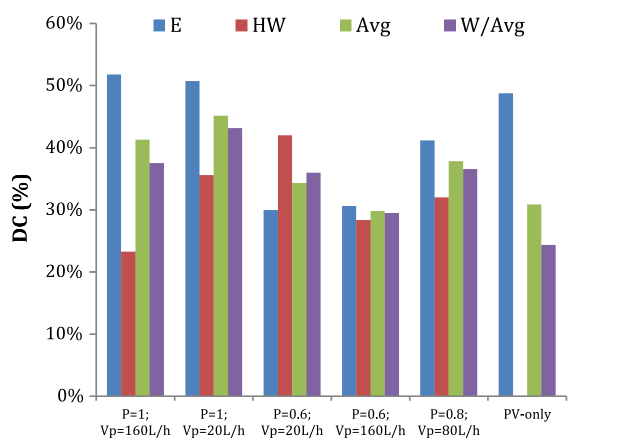

Fig. 11. Percentage of electrical (E), hot water (HW), average (Avg) and weighted average (W/Avg) household demands covered by selected PVT configurations and comparison with the PV-only system. Reproduced from Herrando et al. [14].

drawn from Fig. 14(a) is that, even though the upfront cost of the PVT system with $P = 0.6$ and $V_P = 20$ L/h is closer to the one achieved for the PVT system with $P = 1.0$ and $V_P = 20$ L/h thanks to this optimum a-RHPP, the DPB is significantly higher in the former case due to its larger annual costs. Fig. 14(b) and Table 9 corroborate that, due to the larger annual costs of the other PVT configurations with $P < 1$, even though they have a smaller upfront cost than the PVT configuration with $P = 1.0$, it is necessary to decrease their upfront costs by more than 50% of its actual cost to achieve the same DPB as the PV-only system.

5. Further discussion and conclusions

5.1. PVT system potential

Solar-thermal and PV systems are generally recognised as technologies that can play an important role in an evolution towards a more diverse, secure and decarbonised energy future [11]. Their current respective markets are experiencing a significant (i.e. exponential) growth, which can be attributed to policy support by various Governments and the increasing environmental awareness of the end-user. As a consequence, the integration of these technologies into a hybrid system also has great potential and deserves attention, not only in combining the advantages of the two technologies in a single system capable of providing both an electrical and a thermal output from the same roof space (crucial in area-constrained geographies), but also in the synergistic manner in which the removal of heat for hot-water generation cools and increases the efficiency of the PV cell. A similar growth in the demand for PVT systems may be expected, with the domestic sector having the largest market potential at about 90% of the current market according to Affolter et al. [26]. However, assuming a desire to realise this potential has been established, policymakers must then consider pathways for the promotion of these technologies in order to make them a cost-competitive and commercially attractive alternative energy solution [11].

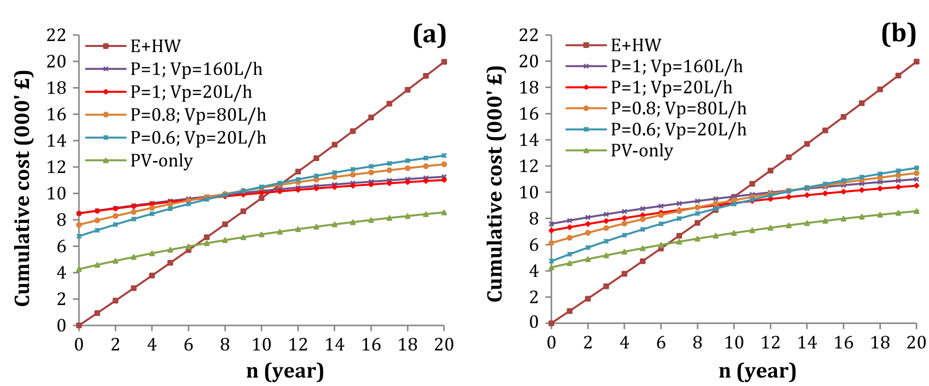

Fig. 12. Comparison of the cumulative costs of the different PVT configurations studied to that of the PV-only system with a discount rate of $d = 0.08$, as well as to that of the conventional scenario (electricity + hot water costs (squares)) with a discount rate of $d_c = 0.025$, when: (a) the Renewable Heat Incentive (RHI) is implemented and (b) the RHI is given as a one-off voucher at the beginning of a system's lifetime, in the form of an 'augmented' Renewable Heat Premium Payment (a-RHPP). An inflation rate of $i = 0.032$ is used throughout.

Table 6
Summary of the economic assessment for the different PVT configurations and the PV-only system studied when the Renewable Heat Incentive (RHI) is considered. A 20-year system lifetime, an inflation rate of $i = 0.032$, a discount rate of $d_c = 0.025$ for the conventional system (grid electricity and gas-boiler hot water), and a discount rate for the PVT system of $d = 0.08$ are assumed. The best solution in each row corresponding to a particular parameter/category appears highlighted (bold and italic).

	$P = 1$; $V_P = 160$ L/h	$P = 1$; $V_P = 20$ L/h	$P = 0$ .6; $V_P = 20$ L/h	$P = 0.8$; $V_P = 80$ L/h	PV-only
E_{PVT} (kW$_e$ h/year)	***2390***	2290	1360	1880	2190
Q_{PVT} (kW$_{th}$ h/year)	670	960	***1130***	840	0
DC_E (%)	***51.8***	50.7	30.0	41.2	48.7
DC_{HW} (%)	23.3	35.6	***42.0***	32.0	0.0
DC_{wav} (%)	41.3	***45.2***	34.4	37.8	30.9
DC_{av} (%)	37.5	***43.2***	36.0	36.6	24.4
C_0 (£)	8480	8480	6750	7620	***4270***
A_i (£/year)	***283***	290	592	443	345
RHI (£/year)	60	85	***100***	74	0
A_{inet} (£/year)	223	***205***	492	369	345
DPB (year)	10.6	10.4	11.1	11.0	***6.8***
NPV (£'000)	11.3	11.0	12.9	12.2	***8.6***
L (£'000/year)	1.15	1.12	1.31	1.24	***0.87***
LPC (p/kW h)	37.5	***34.6***	52.8	45.9	39.8
LCC_E (£'000/DC_E)	2.22	2.21	4.38	3.02	***1.79***
LCC_{HW} (£'000/DC_{HW})	4.92	3.16	***3.12***	3.89	–
LCC_{wav} (£'000/DC_{wav})	2.78	***2.49***	3.81	3.29	2.83
LCC_{av} (£'000/DC_{av})	3.06	***2.60***	3.65	3.40	3.58

Table 7
Summary of the economic assessment for the different PVT configurations and the PV-only system studied when the RHI is given as a one-off voucher at the beginning of the system's lifetime, in the form of an "augmented Renewable Heat Premium Payment" (a-RHPP). A system lifetime of 20 years, an inflation rate of $i = 0.032$, a discount rate of $d_c = 0.025$ for the conventional system (grid electricity and gas-boiler hot water), and a discount rate for the PVT system of $d = 0.08$ are assumed. The best solution in each row corresponding to a particular parameter/category appears highlighted (bold and italic).

	$P = 1$; $V_P = 160$ L/h	$P = 1$; $V_P = 20$ L/h	$P = 0$ .6; $V_P = 20$ L/h	$P = 0.8$; $V_P = 80$ L/h	PV-only
E_{PVT} (kW$_e$ h/year)	***2390***	2290	1360	1880	2190
Q_{PVT} (kW$_{th}$ h/year)	670	960	***1130***	840	0
DC_E (%)	***51.8***	50.7	30.0	41.2	48.7
DC_{HW} (%)	23.3	35.6	***42.0***	32.0	0.0
DC_{wav} (%)	41.3	***45.2***	34.4	37.8	30.9
DC_{av} (%)	37.5	***43.2***	36.0	36.6	24.4
C_0 (£)	7590	7080	4750	6130	4270
A_i (£/year)	***274***	276	572	429	345
RHI (£/year)	60	85	***100***	74	0
DPB (year)	10.0	9.5	9.2	10.7	6.8
NPV (£'000)	11.0	10.5	11.9	11.5	8.6
L (£'000/year)	1.12	1.07	1.21	1.17	0.87
LPC (p/kW h)	36.6	***33.0***	48.7	43.1	39.8
LCC_E (£'000/DC_E)	2.16	2.11	4.03	2.84	1.79
LCC_{HW} (£'000/DC_{HW})	4.81	3.01	***2.88***	3.65	–
LCC_{wav} (£'000/DC_{wav})	2.71	***2.37***	3.52	3.09	2.83
LCC_{av} (£'000/DC_{av})	2.98	***2.48***	3.36	3.19	3.58

In Herrando et al. [14] a commercially available PVT/w system based on a sheet-and-tube collector design was modelled, and the system model was used to predict annualised performance in terms of its electrical and thermal outputs (and consequently the coverage of a typical UK household's demand for power and hot water), as well as total CO_2 emission savings relative to the performance of conventional technologies. The influence of two parameters that were expected to affect significantly the system's performance was studied closely in order to identify parameter values that were more appropriate in the particular scenario considered of electricity and hot-water provision to an average household in London, UK. These parameters were the collector cooling-water flow-rate and the covering factor of the collector with PV. The results confirmed the importance of these two system parameters. It was concluded that the covering factor significantly influenced the electrical output and did not have a noteworthy impact on the thermal output, but that the thermal output was sensitive to the collector cooling flow-rate. High covering factors (80–100%) and relatively low cooling flow-rates (20–80 L/h) were recommended as a balanced compromise that can maximise jointly the electrical and hot-water outputs. Ultimately, the best hybrid PVT/w system demonstrated an annual electricity generation of 2.3 MW$_e$ h, or a 51% coverage of the household's electrical demand (compared to an equivalent PV-only value of 49%), plus an annual hot-water heating potential amounting to 1.0 MW$_{th}$ h, or a hot-water demand coverage of up to 36%. This distributed generation of electricity and hot water corresponds to a 14 tonnes displacement of associated fossil-fuel consumption over a lifetime of 20 years and allows a reduction in CO_2 emissions amounting to 16.0 tonnes, both of which are significantly higher than the PV-only equivalent figures; by 18% and 36%, respectively.

5.2. Nominal economic considerations

The present paper complements the above findings with economic analyses, also taking into consideration the financial support for these technologies in the form of incentives. Specifically, the total investment cost required for the installation of a PVT system, as well as the total running costs and operation and maintenance costs incurred were considered. The costs incurred after the installation of a PVT system were compared to the costs of using conventional equivalents consisting of buying electricity from the

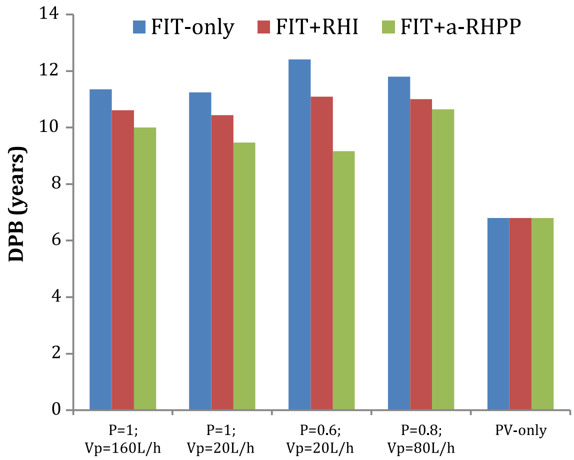

Fig. 13. Discounted Payback Period (DPB) of the different PVT configurations studied and of the PV-only system, with FIT support only, the introduction also of a nominal Renewable Heat Incentive (RHI), and the introduction of an augmented Renewable Heat Premium Payment (a-RHPP). Here, the following values have been employed: a discount rate of $d = 0.08$ for the PVT, a discount rate of $d_c = 0.025$ for the conventional scenario. An inflation rate of $i = 0.032$ is used throughout.

grid and using a mix of technologies (natural gas boilers, electrical heaters and heat pumps) to satisfy the hot-water demand, as per the current average scenario in the UK. In order to gain further insight into the detailed performance of PVT systems over the course of a full year, five combinations of PVT collector flow-rates and covering factors were selected and the outputs throughout the year were evaluated.

The results showed that the running-cost savings due to local electricity microgeneration are influenced strongly by the covering factor, mirroring the significant influence of the covering factor on the PVT system's electrical output. This effect is exacerbated by the fact that the electricity produced can be sold to the grid at a considerably higher price than that at which it is bought from the grid (due to the FITs available in the UK); therefore any time periods with a surplus of electricity notably outweigh ones with a deficit. Conversely, although the running-cost savings associated with hot-water production deteriorate when using higher covering-factor PV designs, the total cost savings are significantly more sensitive to the electrical output due to the higher price of electricity and the FITs, compared to that of hot-water generation and the nominal RHI used in this work. Hence, to maximise the total running-cost savings, high covering-factor values allowing high electrical outputs are recommended. The electrical running-cost savings are not significantly influenced by the collector cooling flow-rate, but the hot-water cost savings improve when this is decreased due to a reduced need for auxiliary heating. Nevertheless, as stated previously, the total cost savings are dominated by the electricity-related energy costs and incentives, so the thermal output and by extension the collector flow-rate do not notably

Table 8
Discounted Payback Period (DPB) of the different PVT configurations studied and comparison with the PV-only system, with FIT support only, the introduction also of a nominal Renewable Heat Incentive (RHI), and the introduction of an augmented Renewable Heat Premium Payment (a-RHPP) (discount rate of PVT $d = 0.08$, discount rate of conventional system $d_c = 0.025$ and inflation rate $i = 0.032$).

	$P = 1$; $V_P = 160$ L/h	$P = 1$; $V_P = 20$ L/h	$P = 0.6$; $V_P = 20$ L/h	$P = 0.8$; $V_P = 80$ L/h	PV-only
DPB: FIT-only	11.4	11.2	12.4	11.8	6.8
DPB: FIT + RHI	10.6	10.4	11.1	11.0	6.8
DPB: FIR + a-RHPP	10.0	9.5	9.2	10.7	6.8

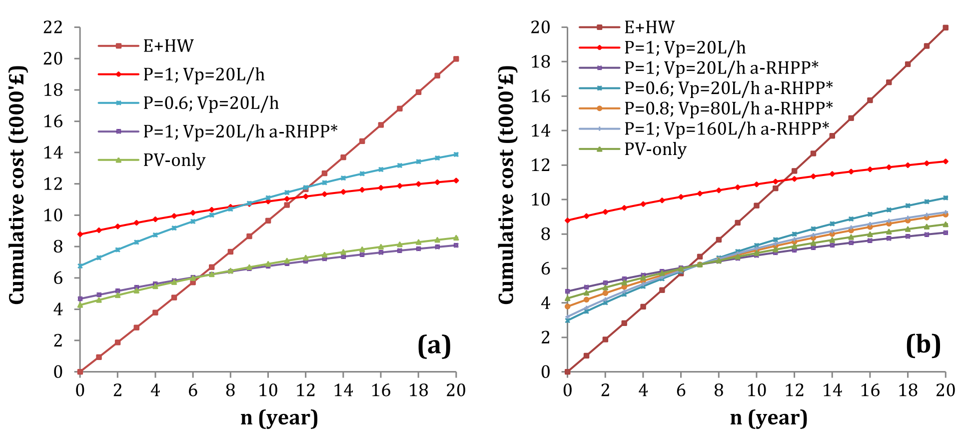

Fig. 14. Comparison of the cumulative costs of the different PVT configurations studied to that of the PV-only system with a discount rate of $d = 0.08$, as well as to that of the conventional scenario (electricity + hot water costs (squares)) with a discount rate of $d_c = 0.025$ and an inflation rate of $i = 0.032$, when the optimum augmented Renewable Heat Premium Payment (a-RHPP*) is given as one-off voucher at the beginning of a system's lifetime.

Table 9
Summary of results concerning the estimation of the optimum augmented Renewable Heat Premium Payment (a-RHPP*) for the different PVT configurations studied (discount rate of PVT $d = 0.08$, discount rate of conventional system $d_c = 0.025$ and inflation rate $i = 0.032$).

	$P = 1$; $V_P = 160$ L/h	$P = 1$; $V_P = 20$ L/h	$P = 0.6$; $V_P = 20$ L/h	$P = 0.8$; $V_P = 80$ L/h
Actual C_0	£8780	£8780	£6750	£7620
Optimum a-RHPP	£5590	£4120	£3780	£3830
C_0 (including a-RHPP*)	£3190	£4670	£2980	£3790
% of actual cost	64%	47%	56%	50%

influence the overall system cost savings for the nominal economic case studied herein.

The studied RHI was responsible for closing the gap between the cumulative costs and payback of PVT and PV-only systems over time, thanks to the payments from the thermal output. As a consequence, the discounted payback period of a promising PVT system with $P = 1.0$ and $V_P = 20$ L/h fell from 11.2 years (for a nominal FIT of 43.3 p/kW h) to 10.4 years (with an introduction of a nominal RHI at a rate of 8.5 p/kW h), although these were still higher than the 6.8 years estimated for the PV-only system.

Sensitivity analyses were also performed to study the influence of the inflation (i) and discount (d) rates on the results. Variations in the discounted payback periods falling inside the range 10–13 years were found when an inflation rate of 3.2% was used and the discount rate was varied from 5% to 10%, and 10–11 years when a higher inflation rate of 6% was tested. The best configuration amongst the PVT system configurations studied is the one with a covering factor of unity and a collector flow-rate of 20 L/h, which achieves a payback of 11.2 years (at $d = 8\%$) and also gives the best all-round economic results, including: a levelised energy production cost of 38 p/kW h and a levelised household-energy coverage cost of £2720 ($d = 8\%$). This is the same configuration that achieved 51% coverage of the total annual electrical demand and 36% coverage of the total hot-water demand of the household. However, this configuration has a significantly longer payback than a c-Si PV-only system with the same peak capacity, which is at 6.8 years, even though a lower amount of the electrical demand is covered by the PV-only system (49%) and all of the energy required to cover the hot-water demand needs to be obtained separately. As a consequence, the levelised costs for the PV-only system are higher: 40 p/kW h and £2,830, respectively ($d = 8\%$).

In conclusion, the design of a PVT collector and the wider system configuration and operation significantly affect its thermal and electrical outputs, and it is not possible to maximise both outputs at the same time, which gives rise to a trade-off between them. In the nominal economic scenario investigated in the present paper, the relative financial costs and benefits of generating electricity (including incentives) are significantly higher than those associated with hot-water generation. This distorts the total/overall running costs of the PVT system, which become strongly affected by the former. In addition, when Government incentives such as FITs are applicable, there is an added benefit from the production of electricity because the system can generate profits when the electricity produced exceeds the demand, therefore making the system more attractive. In this case, cost minimisation is the ultimate goal and the solar system's electricity production is a priority. Nevertheless, heat is also important from an energy and emissions point of view. In fact, heat outweighs electricity consumption by a factor of about 4 (by energy unit) in the UK domestic sector, leading to a need to consider seriously and carefully the potential thermal output from solar-thermal technologies such as PVT, when developing relevant policy.

5.3. Incentive variations and lessons for policy development

One of the main barriers to the installation of PVT systems in the UK concerns their high upfront investment costs, which amount to ~£8800 for a 2.25 kW_P (peak installed electrical capacity) system, compared to ~£4300 for a PV-only system with the same capacity. This can be addressed by making available suitable financing schemes [27]. Therefore, the present paper also studied the economic impact of various alternative incentives relating to the *thermal* output of PVT systems.

An alternative scheme applicable to solar-thermal systems consists of a one-off, upfront voucher for the installation of solar-thermal products. The present results suggest that a £300 payment is an insufficient incentive for PVT technology. Nevertheless, an alternative termed the 'augmented' RHPP was proposed (a-RHPP), which is an amount equal to the total RHI paid over a 20-year lifetime but given as a one-off voucher at the time of installation, assuming a constant thermal output from the system over the 20 years. In this case, the total investment cost of the PVT configurations studied decreases depending on their thermal output. The results show that owing to this incentive the differences between the cumulative costs of the PVT and PV-only systems decrease further, and the payback period of a suitably selected PVT configuration drops (from 11.2) to 9.5 years, approaching but still remaining higher than the 6.8 year payback of the PV-only system. It was further established that the most appropriate PVT configuration ($P = 1.0$; $V_P = 20$ L/h) required a £4120 voucher, or 47% of the installation cost, to match the PV-only payback time, although it was noted that beyond this point the cumulative costs of the PVT system were lower than those of the PV-only system, allowing increased savings to the household. This voucher payment is 2.4 times larger than the a-RHPP (£1700) and also the total RHI paid to the household over this system's 20-year lifetime (based on 8.5 p/kW h). Therefore, it can be concluded that a RHI at a level of approximately 20 p/kW h (or half the FIT rate used in this work for the electrical output) would effectively place PVT technology on par with PV in terms of payback.

Based on all of the aforementioned results and findings, it is possible to conclude that PVT technology has a significant potential to lower emissions and the primary energy consumed in the domestic sector in the UK. PVT systems can provide more than 50% of the electrical demand while also covering around 30–40% of the hot-water demand in a typical 3-bedroom household of 4 inhabitants (in London). These systems are already commercially available, although it has been shown that they can be optimised for particular installations, in particular by varying their PV covering factor and the collector cooling flow-rate. One of the major barriers of PVT-system uptake is their high upfront investment cost, which can make them less attractive than conventional PV-only systems. Our analyses indicate that they do, however, offer certain tangible advantages compared to PV and that it is possible to place these two technologies on a relatively equal footing by monetising their thermal output at a given rate.

In closing, it is emphasised that the present study focuses on the specific case of PVT systems in the UK climate (specifically London), where the temperatures reached on the PVT unit are not too high. This scenario leads to the recommendation for a complete coverage of the solar collector with PV and a low collector cooling flow-rate. One should consider that in other countries with higher solar irradiance (e.g. lower latitudes) it may be necessary to reconsider the covering factor as well as the collector cooling flow-rate that optimise the technical and economic proposition of the PVT technology.

Acknowledgment

This work was supported by the Research Councils UK (RCUK) [grant number EP/E500641/1]. Data supporting this publication can be obtained on request from cep-lab@imperial.ac.uk.

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