PERFORMANCE ASSESSMENT AND COMPARISON OF SOLAR ORC AND HYBRID PVT SYSTEMS FOR THE COMBINED DISTRIBUTED GENERATION OF DOMESTIC HEAT AND POWER

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ABSTRACT

Solar-thermal collectors and photovoltaic panels are effective solutions for the decarbonisation of electricity and hot water provision in dwellings. In this work, we provide the first insightful comparison of these two competing solar-energy technologies for the provision of combined heating and power (CHP) in domestic applications. The first such system is based on an array of hybrid PV-Thermal (PVT) modules, while the second is based on a solar-thermal collector array of the same area (based on a constrained roof-space) that provides a thermal-energy input to an organic Rankine cycle (ORC) engine for electricity generation. Simulation results of the annual operation of these two systems are presented in two geographical regions: Larnaca, Cyprus (as an example of a hot, high-irradiance southern-European climate) and London, UK (as an example of a cooler, lower-irradiance northern-European climate). Both systems have a total collector array area of 15 m^2, equivalent to the roof area of a single residence, with the solar-ORC system being associated with a lower initial investment cost (capex) that is expected to play a role in the economic comparison between the two systems. The electrical and thermal outputs of the two systems are found to be highly dependent on location. The PVT system is found to provide an annual electricity output of 2090 kWh$_e$ yr^{-1} in the UK, which increases to 3620 kWh$_e$ yr^{-1} in Cyprus. This is equivalent to annual averages of 240 and 410 W$_e$, respectively, or between 60% and 110% of household demand. The corresponding additional thermal (hot water) output also increases, from 860 kWh$_{th}$ yr^{-1} in the UK, to 1870 kWh$_{th}$ yr^{-1} in Cyprus. It is found that the solar-ORC system performance is highly sensitive to the system configuration chosen; the particular configuration studied here is found to be limited by the amount of rejected thermal energy that can be reclaimed for water heating. The maximum electrical output from the solar-ORC configuration explored in this study is 450 kWh$_e$ yr^{-1} (50 W$_e$ average, 14% of demand) for the UK and 850 kWh$_e$ yr^{-1} (100 We average, 26% of demand) for Cyprus, however, the study helps to identify aspects that can lead to significant improvement relative to this estimate, and which will be at the focus of future work. An economic analysis is also undertaken to investigate the installed costs and lifecycle costs of the two systems. Without financial incentives both systems show long payback periods (14 years in Cyprus and 18 years in the UK for the PVT, and >20 years for the solar-ORC).

NOMENCLATURE

A	[m^2]	Area
a_1	[m^{2}K/W]	Collector efficiency coefficient
a_2	[m^{2}K^2/W]	Collector efficiency coefficient
C	[J/m^2/K]	Effective heat capacity
d	[-]	Discount rate
D	[-]	Annual demand provision, diameter
G	[W/m^2]	Irradiance
i	[-]	Inflation rate, simulation time-step
J	[€]	Cost
K_θ	[-]	Incident angle modifier
L	[m]	Length
M	[kg]	Mass
P	[W]	Electrical power
Q	[J]	Energy
T	[K]	Temperature
t	[s]	Time
U	[W/Km^2]	Heat loss coefficient
V	[m^3]	Volume
W	[J]	Work
Special characters		
β	[K^{-1}]	PV cell temperature coefficient
η, η_0	[-]	Efficiency, zero-loss efficiency
Subscripts		
a		Ambient, annual
b		Beam irradiance
aux		Auxiliary
c		Collector (array), capital expenditure
comp		Components
cond		Condensation
db		Deadband
d		Demand, diffuse irradiance
e		Electricity
exp		Expander
fan		Fan
gen		Generator
hx		Heat exchanger
hw		Hot Water
i		Inlet
main		Mains water
mod		Module
no		Normal operating
o		Outlet
pp		Pump
sup		Supply
t		Tank
th		Thermal

INTRODUCTION

The distributed generation of heat and power from small-scale renewables has a prominent role to play in future energy and resource security, and emission reductions [1]. The UK has seen significant growth in installed capacity of solar photovoltaic (PV) systems over the last decade, driven by the fall in cost of PV panels and the successful introduction of the feed in tariff (FIT) incentive scheme for domestic installations. Solar thermal collectors meanwhile are a cost-effective and mature technology for the provision of water and space heating. Cyprus is the world's solar-thermal leader in per-capita terms, at 0.55 kW_{th} in 2013. New developments in high performance non-concentrating collectors are providing an opportunity to extend applications to higher temperature processes such as desalination, and absorption refrigeration [2]. Two emerging technologies that show strong potential for use in distributed solar *combined* heat and power systems are the PV-thermal (PVT) hybrid collector and the organic Rankine cycle (ORC).

The PVT hybrid collector system employs a PV module and thermal collector, where the PV module is in thermal contact with a rear thermal absorber (normally a copper sheet with a serpentine flow arrangement for the heat transfer fluid) [3-5]. These modules have a lower temperature output than conventional flat plate collectors, but a higher electrical efficiency as the solar cells operate at a reduced temperature compared to a conventional PV module [6]. In an earlier paper, Guarracino et al. [7] presented a 3-dimensional thermal model of a PVT collector implemented into a wider domestic combined heat and power (CHP) system model allowing the comparison of various configurations of PVT collector. As part of the study, unglazed, glazed and double glazed collectors were compared in terms of their annual electrical and thermal performance. It was found that a 15 m^2 unglazed PVT array could provide ~1.8 MWh of electricity annually and cover ~25% of the hot water demand.

An ORC system, meanwhile, is based on a conventional Rankine cycle but uses an organic compound instead of water as the working fluid. This allows ORC engines to be designed and built for efficient operation at smaller scales and lower temperatures than steam-Rankine engines without the need for complex and expensive turbomachinery. By selecting an appropriate working fluid, the cycle can be matched to a particular heat source, inviting the possibility for integration with low cost solar collectors. In an earlier work, Freeman et al. [8] presented a model of a solar-CHP system based on solar thermal collectors and an ORC engine and simulated its annual performance in a UK setting. The system was configured to prioritise the generation of electrical energy, with the ORC system evaporator located upstream of the hot water storage tank and was found to produce in the region of ~0.8 $MWh_e\ yr^{-1}$ from a 15 m^2 evacuated tube collector array, but at a lower upfront capital cost than the aforementioned PVT system.

In this paper we present a comparison study of two domestic-scale solar CHP systems. The first is based on an array of PVT collectors, while the second is based on an ORC engine taking a thermal input from an array of solar thermal collectors in a slightly different configuration to that considered earlier in Ref. [8]. To the best of the authors' knowledge, no detailed techno-economic study has previously been undertaken to assess and compare the potential of these competing solar technologies in a domestic-scale CHP application. Both systems will be analysed in terms of their electrical and thermal outputs over a 1-year simulation period in the climates of London, UK and Larnaca, Cyprus. An economic analysis will also be performed on the two systems and used to compare them in terms of life-cycle costs and the generation costs of electrical and thermal energy.

MODELLING METHODOLOGY

The two S-CHP system layouts are shown in Figs. 1 and 2. Both systems are constricted by the available roof area and hot water storage volume available in the dwellings in which they are installed. The available area for the solar collector array is 15 m^2, and the volume of the hot water storage tank is limited to 150 L.

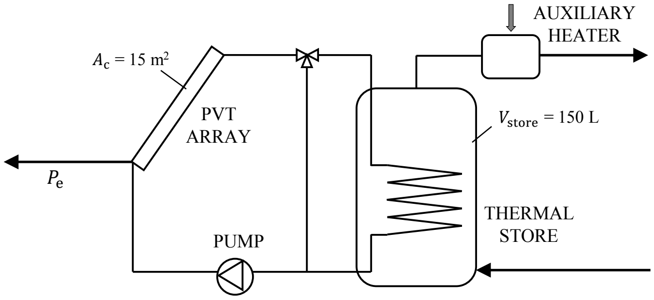

Figure 1 Schematic of the PVT-based solar CHP system

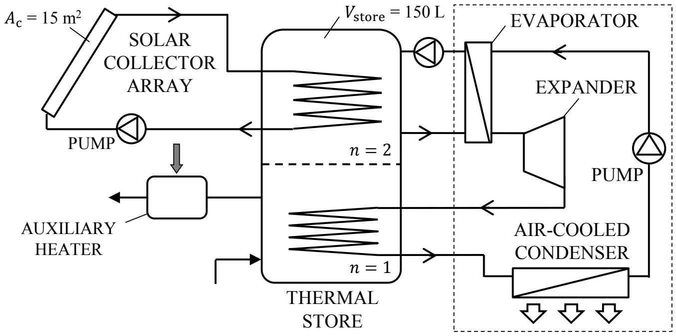

Figure 2 Schematic of the ORC-based solar CHP system

The collectors are orientated due south for both systems, at the optimal inclination angle of 38º [4]. The required water delivery temperature is 60 ºC and the mains top-up water temperature to the cylinder is 10 ºC [3]. The tank is located indoors and exchanges heat with its environment, assumed to be at a constant air temperature of 20 °C. When the temperature of water leaving the cylinder is less than the required delivery temperature, auxiliary heating is supplied to the water stream as necessary. For both systems, the solar collectors are based on real collectors and modelled using manufacturer's thermal efficiency curves, shown in Fig. 3 and described by the equation:

$$\frac{\dot{Q}_{\mathrm{th}}}{A} = \eta_0\left(K_{\theta,\mathrm{b}}G_{\mathrm{b}} + K_{\theta,\mathrm{d}}G_{\mathrm{d}}\right) - a_1(\bar{T}_{\mathrm{c}} - T_{\mathrm{a}}) - a_2(\bar{T}_{\mathrm{c}} - T_{\mathrm{a}})^2 - C\frac{\mathrm{d}\bar{T}_{\mathrm{c}}}{\mathrm{d}t} \quad (1)$$

where C is a lumped thermal capacity parameter used for calculating performance under transient conditions, and determined according to EN 12975-2 [9].

PVT SYSTEM MODEL

The PVT system is composed of 10 glazed c-Si PVT modules. The thermal and electrical characteristics of the modules are taken from manufacturer's data sheets and reported in Table 1 and Fig. 3. The system operates with a fixed flow-rate and the temperatures are monitored at the top of the tank, at the collector outlet and at the collector inlet. Solar fluid flows to the heat exchanger coil located in the tank only when the fluid leaving the collector T_o is higher than $T_\mathrm{t} + 10$ °C and is allowed to heat up the tank until $T_\mathrm{o} \leq T_\mathrm{t} + 1.5$ °C. The electricity output of the PVT array is modelled using Eq. (2). The equation takes into account the loss in electrical efficiency with increasing module operating temperature, calculated using Eq. (3).

$$P_\mathrm{e} = AG\eta_\mathrm{e}[1 - \beta(T_\mathrm{mod} - 25)] \tag{2}$$

$$T_\mathrm{mod} = T_\mathrm{a} + (T_\mathrm{no} - 20)G/800 \tag{3}$$

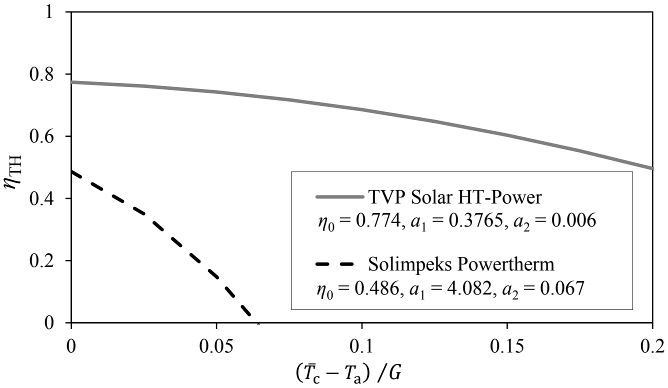

Figure 3 Thermal efficiency curve (and coefficients) for the PVT and EFP collectors [2,14-15].

Table 1: System model parameters

General solar system parameters			
Tilt	38°	T_main	10 °C
V_t	150 L	T_sup	60 °C
$U_\mathrm{hx,coil}$	180 W m^{-2} K^{-1}		
Parameters specific to the PVT system			
A_mod	1.44 m^2	β	0.004
C	13.96 J m^{-2} K^{-1}	T_no	47 °C
η_e	0.13	U_t	3 W m^{-2} K^{-1}
Parameter specific to the ORC system			
A_mod	1.95 m^2	η_pp	0.65
C	7.51 J m^{-2} K^{-1}	η_exp	0.75
U_t	0.3 W m^{-2} K^{-1}	η_gen	0.9
$U_\mathrm{hx,plate}$	400 W m^{-2} K^{-1}	ΔT_pinch	5 K
ΔT_pinch	5 K	Working fluid	R245fa
ΔT_db	10 K		
$\dot{W}_\mathrm{fan}$	$54.5 + 0.154 \cdot \dot{Q}_\mathrm{cond}/\Delta T_\mathrm{pinch}$ [10]		

ORC system model

The ORC system is interfaced with the solar collector array via the hot water tank, as shown in Fig. 2, which also serves as a buffer vessel for the thermal input to the cycle. An evacuated flat plate (EFP) collector array is used to provide thermal energy for the ORC system. The pump and expander of the ORC system operate with fixed flow-rates and therefore are represented by fixed isentropic efficiencies. The water from the hotter top segment of the tank is used to evaporate the working fluid externally in a plate heat exchanger and is then sent back to the tank. Heat is rejected from the cycle primarily by a coil located in the cooler bottom segment of the tank. A dry-air cooling tower is used to provide the remainder of heat rejection to ambient air when required. The plate heat exchanger and cooling tower are both modelled using a pinch temperature difference, and sized accordingly. The cold water inlet and hot water outlet ports are both located in the bottom segment of the hot water tank, in order to prioritise the use of higher grade thermal energy for input to the ORC. The maximum water storage temperature for the bottom segment is 80 ºC while for the top segment it is defined by the boiling point of water at the water pressure in the tank (assumed to be 2 bar(g)). The ORC switches on when the top of the tank reaches the temperature required for evaporation of the working fluid, plus a deadband. The ORC then switches off when the temperature at the top of the tank drops below the lower limit of the deadband. The net electrical output from the ORC system is:

$$P_\mathrm{e,net} = \eta_\mathrm{gen}\dot{W}_\mathrm{exp} - \dot{W}_\mathrm{pp} - \dot{W}_\mathrm{fan}. \tag{4}$$

Annual simulation

Simulations are performed using annual solar irradiance and air temperature profiles from ASHRAE [11] for London, UK and Larnaca, Cyprus. These two locations have contrasting solar resources, with an annual solar insolation of 2246 kWh m^{-2} (256 W m^{-2}, average) for Larnaca compared to 1217 kWh m^{-2} (139 W m^{-2}, average) in London. A numerical calculation time-step of $\Delta t = 5$ min is found to be suitable for the simulations. A hot water demand profile is implemented that is based on hourly domestic hot water consumption data from the Energy Saving Trust [12]. For simplicity of analysis, both models will use the same 24-hour hot water demand profile representative of an average UK home on an average day. The same daily demand profile will be used for each day of the year and provides a total daily volume of water drawn from the storage tank of 122 L day^{-1}. As a further simplification, the electrical output is not dependent on a demand profile, and both systems will output electricity when there is sufficient solar radiation (or in the case of the ORC engine, a sufficient temperature of water in the thermal store). It will thus be assumed that all electrical energy generated is consumed locally for domestic use. The annual electricity demand provision is:

$$D_\mathrm{e} = \sum \dot{Q}_{\mathrm{e}(i)}\Delta t / Q_\mathrm{e,d}, \tag{5}$$

where annual electricity demand $Q_\mathrm{e,d}$ is taken as 3300 kWh yr^{-1} [3]. The hot water demand provision is:

$$D_\mathrm{th} = \sum \dot{Q}_{\mathrm{hw}(i)}\Delta t / \left(Q_{\mathrm{hw}(i)} + Q_{\mathrm{aux}(i)}\right). \tag{6}$$

Economic analysis

The system costs are divided into capital costs and annual incurred running costs. The costing factors used to calculate the capital costs are presented in Table 3. The annual incurred costs are comprised of the operations and maintenance (O&M) costs, plus the costs of auxiliary electricity and water heating. Auxiliary heating is assumed to be from a gas boiler with an efficiency of 97% [5]. The systems will be compared in terms of their levelised production costs of electricity, hot water and combined heat and power, over an assumed 20-year system lifetime:

$$LPC = NPV_N / \sum_{N=1}^{N} [Q/(1+d)^N]. \quad (7)$$

where Q is the annual production of either electrical or thermal energy or the sum of both. The net present value (NPV) represents the cumulative cost of the system over its lifetime and is calculated as the sum of the capital cost and the present worth value of the annualised costs for each year of operation:

$$NPV_N = J_\mathrm{c} + \sum_{N=1}^{N} J_\mathrm{a}(1+i)^{N-1}/(1+d)^N. \quad (8)$$

The levelised cost and payback time of the system is highly dependent on the choice of discount rate for the analysis. For solar thermal systems, literature values are in the range of 5-10 % [5]. A discount rate of 8% and an inflation rate of 3.5% will be used for this analysis. Separate levelised costs of heating and power are found by splitting the capital and running costs between the hot water generating components and the electricity generating components of the PVT and solar-ORC systems. For simplicity it is assumed that the cost of the basic solar thermal hot water system is €4000 [13], and the rest of the capital cost of the system is allocated to electricity generation. The O&M costs meanwhile are split evenly between the hot water and electricity generating sub-systems.

Table 2: Capital costs incurred for the PVT system and for the solar ORC system, taken from Refs. [5,10,14-24].

PVT costs, €		
Collectors	$300 \cdot A_\mathrm{c}$	[14]
Electrical components (inverter, cables etc.)	$1.050 \cdot P_\mathrm{e}$	[16]
Solar-ORC component costs, €		
Collectors	$200 \cdot A_\mathrm{c}$	[15,17]
Plate heat exchangers	$185 + 183 \cdot A_\mathrm{c}$	[18]
ORC pump	$900 \cdot (\dot{W}_\mathrm{pp}/300)^{0.25}$	[10]
ORC expander	$1.5 \cdot (199 + 281 \cdot \dot{V}_\mathrm{s})$	[19-20]
Liquid receiver (5 L)	110	[10]
Dry-air cooling tower	$90 \cdot \dot{Q}_\mathrm{cond}$	[21]
Generator	500	[22]
Working fluid	$20 \cdot M$	[10]
Ancillary component and running costs, €		
Hot water cylinder (150 L)	1060	[5]
Solar collector circulation pump	215	[23]
Expansion vessel	60	[24]
Copper pipe/coil	$(3027 \cdot D^2 + 97 \cdot D) \cdot L$	[21]
Valves & connections	$8 \cdot A_\mathrm{c}$	[23]
Roof fixings	$16 \cdot A_\mathrm{c}$	[23]
Controls	300	[23]
Installation	$0.16 \cdot J_\mathrm{comp}$	[5]
Operations & maintenance (per year)	$0.01 \cdot J_\mathrm{capex}$	[5]
Utility prices of gas and electricity displaced by system		
Electricity (standard rate)	14.05 €/kWh$_\mathrm{e}$	[5]
Gas	4.29 €/kWh$_\mathrm{th}$	[5]

The economic assessment does not consider the potential for revenue generation from low-carbon technology incentive schemes such as Feed-in Tariffs (FIT) or renewable energy payments. This is due to the significant differences in such incentive mechanisms between the UK and Cyprus, and the rapid changes in the available tariffs over recent years. Cyprus has no specific FIT, although the government offers a capital-cost contribution of 900 € per kW for domestic PV installations and users are billed according to their net electricity consumption over the metering period [25]. The UK FIT premium payment meanwhile is currently 4.32 p (5.5 ¢) per kWh^{-1} for < 10 kW PV systems installed on dwellings, but has decreased from 43.3 p (55 ¢) per kWh^{-1} since its introduction 2010 [13]. The UK Domestic Renewable Heat Incentive (RHI) for thermal energy generated by solar hot water systems was introduced in 2014 and the current value of the tariff is 19.51 p (24.8 ¢) per kWh^{-1} [13].

RESULTS

System performance

The results of the annual simulations are presented in Table 3. Initially both systems were simulated with a tank insulation U-value of 3.0 W m^{-2} K^{-1}. However the electrical output of the ORC system, which requires thermal input temperatures of 90-100 ºC for optimal performance, was found to be significantly impeded by thermal losses accounting for approximately one quarter of the solar thermal energy input to the tank. Thus the insulation U-value was improved to 0.3 W m^{-2} K^{-1}, which reduced the thermal losses by 85% and resulted in a 26% improvement in electrical performance and a 21% improvement in hot water output. In general, the performance of the solar-ORC system showed high sensitivity to the system configuration chosen.

The simulation results show that the PVT system is able to produce more than four times more electrical energy annually than the ORC system in the UK climate simulations, despite the average thermal efficiency of the EFP collector being four times that of the PVT collector. The annual electrical output of the ORC system in the UK climate is significantly lower than that predicted in an earlier study by the same authors [8], in which an alternative system configuration was investigated. The earlier work featured a counter-flow water-cooled condenser to achieve a low condensation temperature (17 ºC, compared to 30 ºC in the present study); and the evaporator heat exchanger received a non-buffered thermal input directly from the solar array, which allowed the use of a higher evaporation temperature at the expense of a more intermittent operation.

The primary cause of the low electrical and thermal output for the ORC system compared to the PVT system is the proportion of the total thermal energy rejected to air. Of the total solar thermal energy transferred to the tank (24,000 MJ yr^{-1} for ORC system in the UK climate, compared to 5,000 MJ yr^{-1} for the PVT system), 11% is converted to shaft work in the ORC, 11% is reclaimed as useful thermal energy for water heating and 74% is rejected to air in the cooling tower. This also results in a significant decrease in the net electrical power output as a result of the cooling tower fan power consumption, which annually is equal to 28% of the gross ORC electrical output. The PVT system on the other hand is able to utilise 82% of the solar thermal energy absorbed by the collector for useful water heating, with the remainder accounted for only by thermal losses from the tank. The results reported for the UK in Table 4 are for an ORC condensation temperature of 30 °C, which is optimal for maximum net electrical power from the system. By adjusting the condensation temperature from 30 °C to 60 °C, a 76% increase in hot water output can be achieved, at the expense of a 54% reduction in the electrical work output from the cycle.

Table 3 Results from the annual simulations of the PVT and ORC systems in the climates of UK and Cyprus.

	London simulation		*Larnaca simulation*	
	PVT	ORC	PVT	ORC
$Q_{\mathrm{e,net}}$, kWh yr^{-1}	2092	446	3615	847
Q_{th}, kWh yr^{-1}	855	757	1866	1518
D_e	63%	14%	109%	26%
D_{th}	33%	29%	72%	59%

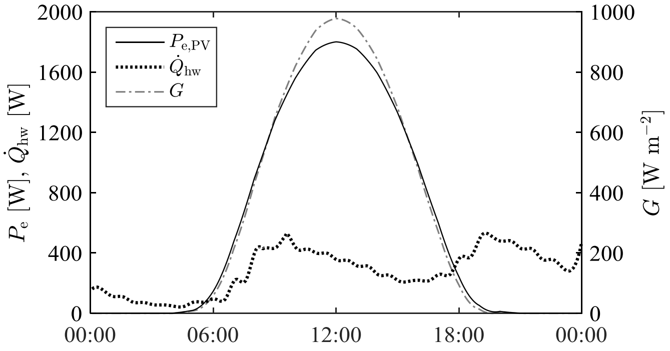

Figure 4 Clear-sky daily operation profile of PVT system showing electrical and thermal outputs

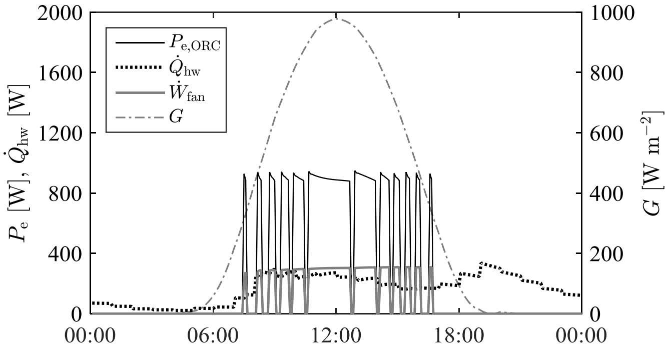

Figure 5 Clear-sky daily operation profile of solar ORC system showing electrical and thermal outputs and also showing fan power consumption for the cooling tower

Figures 4 and 5 show comparison plots for the PVT and ORC systems operating in the UK climate on a clear-sky day. The PVT system electrical output varies with solar irradiance intensity, peaking at 1.8 kW under maximum irradiance, while the ORC electrical output is dependent on the temperature of the thermal store within the deadband limits of operation and produces a gross instantaneous electricity output of 880-950 W, (while fan power consumption for the cooling tower, also shown, is ~300 W). The ORC experiences on-off switching in the morning and afternoon, but is able to maintain a continuous period of operation of more than two hours during the middle of the day. In total the ORC system produces an electrical output for 6.4 hours of the day, compared to 16.9 hours for the PVT system where $P_{\mathrm{e}} > 0$, or 10.2 hours where $P_{\mathrm{e}} > 500$ W$_{\mathrm{e}}$.

Life-cycle costs

The capital costs of the PVT system are high due to the present high price of the PVT collectors. However, the technology is less mature than PV and solar thermal-only modules, and therefore it may be expected to fall in the future as more suppliers enter the marketplace. The ORC system cost is spread over a wider range of items, which represents several possible opportunities for cost saving. However, the reason for the high levelised cost of the ORC system is primarily the low quantities of electricity and thermal energy delivered as outputs and the large amount of thermal energy wasted by rejection to air, which also adds to the costs associated with the cooling tower. The tank is a significant cost component for both systems; for the PVT system the use of a cheaper open-vented tank may reduce the total system cost however the ORC system requires an unvented tank that can store the water at pressure in order to prevent boiling at the higher storage temperatures encountered.

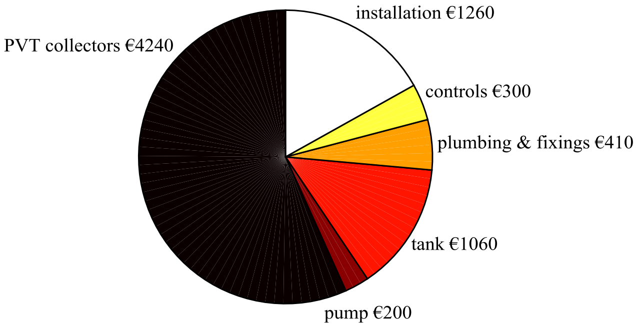

Figure 6 Breakdown of capital costs for the PVT system

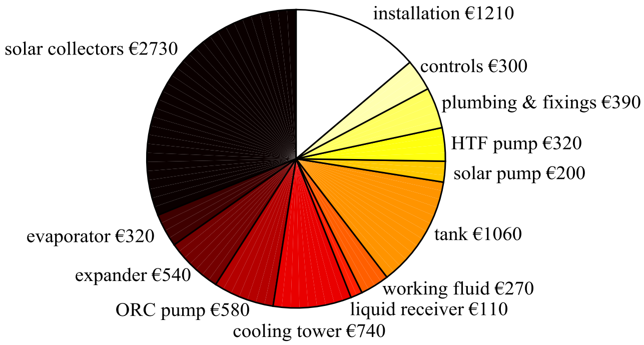

Figure 7 Breakdown of capital costs for the solar ORC system

Due to its low electricity output, the levelised costs of the solar-ORC system are very large when compared with alternative renewable energy systems (~€0.1/kWh$_{\mathrm{e}}$ and ~€0.2/kWh$_{\mathrm{e}}$ for large-scale solar PV and solar thermal, respectively). Although the capital cost of this system is lower than the PVT, the low percentage of electricity and hot water demand covered means that the system does not achieve payback within the lifetime considered here, while the PVT system can be expected to recover its initial investment cost after 14-18 years of operation.

Table 4 Life-cycle cost analysis of energy from the PVT and ORC systems in the climates of UK and Cyprus.

	London simulation		*Larnaca simulation*	
	PVT	*ORC*	*PVT*	*ORC*
Initial investment cost, €	9440	8760	9440	8710
Levelised production cost of heating and power, €/kWh	0.50	1.48	0.22	0.68
Levelised cost of electricity, €/kWh$_e$	0.46	2.67	0.19	1.29
Levelised cost of water heating, €/kWh$_{th}$	0.76	0.78	0.28	0.34
System payback time, yrs	18	>20	14	>20

CONCLUSION

Two systems for the provision of combined heating and power from solar energy have been compared by way of an annual simulation: a hybrid PV-Thermal (PVT) system and an organic Rankine cycle (ORC) heat engine system. The PVT system has been found to cover up to 60% of the annual demand for electricity and 30% of the demand for water heating in the UK for a capital cost of €9400. When simulated in the climate of Cyprus, the system performance improves significantly with annual provision equivalent to 110% of electricity demand and 70% of hot water demand. Despite the maturity of PV and solar hot water systems, the capital cost of the PVT system is high at present, and the levelised cost of electricity is found to be more than four times that for conventional solar PV, without considering government incentive schemes. Nevertheless, considering only the energy bill savings, the system payback time is less than 20 years. The ORC system on the other hand is found to cover only 14% of the demand for electricity in the UK simulation (26% in Cyprus) plus 30% of hot water (60% in Cyprus) for a capital cost of €8700. The ability to recover thermal energy for water heating is limited by the condensation temperature of the cycle, leading to a trade-off between thermal and electrical energy output. If electricity output is prioritised by setting the condensation temperature low, a greater proportion of heat must be rejected by secondary means (i.e. air cooling). The performance of the solar-ORC system showed high sensitivity to the configuration chosen, which suggests that this should be a key area of interest.

An aspect not considered in the analysis is operation in an off-grid, or non-interconnected zone (NIZ) setting. Under such a scenario, electricity produced at times of no local demand could not be exported to a national grid for use elsewhere. The ability of the hot water tank to store energy for input to the ORC is a possible advantage in such a scenario compared to the PVT system which would require battery storage at a typical cost of ~€200 kWh [26]. The use of hourly climate data is also a limitation for the assessment of system performance in the UK and other northerly climates that experience short time-scale variations in irradiance due to passing clouds. Future work will investigate the effect of these shorter time-scale phenomena by experimental means.

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